111-20
3815
40P

NASA Contractor Report 189148
SPI-39-10

Non-Isolated 30 kW Class Arcjet PCU

See-Pok Wong and Edward J. Britt
Space Power, Incorporated
San Jose, California

March 1994

Prepared for
Lewis Research Center
Under Contract NAS3-25609

National Aeronautics and
Space Administration

NON-ISOLATED 30 kW CLASS ARCJET PCU

Su-pok Wong and Edward J. Britt
Space Power, Inc.
San Jose, California

ABSTRACT

A 30 kW class arcjet Power Conditioning Unit, PCU, was built and tested on this Phase II SBIR contract. The PCU is an improved version of two previously developed PCU's. All of these units are 3-phase, 20 kHz buck regulators with current mode feed back to modulate the duty cycle to control the arcjet current at any selected operating point. The steady state control can assure arcjet stability despite the negative dynamic resistance of the arc discharge.

The system also has a circuit to produce a high voltage start pulse to breakdown the gas and initiate the arc. The start pulse is formed by temporarily switching a short current path across the output terminals with a special solid state switching array. The switches then open rapidly, and the energy stored in the output inductors of the buck regulator produces a pulse of ~2500 V for ~500 nsec.

The system was tested and modified until the transition to steady operation occured after start up with a very small surge current overshoot. The system also can withstand a direct short circuit across the output without damage. The automatic feed back control simply reduces the duty cycle to hold the current at the set point. When the short is removed the full power output is immediately restored.

This latest version arcjet PCU is conduction cooled to remove waste heat by conduction to the base plate. This unit is closer to flight a type of design than the previous functional bread boards. Waste heat is small because the PCU has a very high efficiency, ≥ 96%.

The PCU was extensively tested with resistor loads to simulate operation with an arcjet. The unit was tested with ammonia arcjets at the Jet Propulsion Laboratory. Approximately 400 hours of testing were completed, with several starts. Many hours were also demonstrated with resistive loads. Some testing with hydrogen arcjets was also carried out at NASA LeRC. This system concept is now the design base for the ATTD program.

INTRODUCTION

ARCJET APPLICATION

Arcjet thrusters are the leading concept for electric propulsion on the SP-100 space nuclear reactor demonstration mission. This and other missions planned for the 1990's are the precursors of larger, more powerful satellites. These satellites will require the high performance capabilities of arcjet propulsion systems to perform orbit transfer and other maneuvers. An important capability of the system is to operate for long periods of time and to withstand repeated startups. This program focuses on providing a reliable and efficient source of conditioned electric power to the thruster and a means of starting the arcjet repeatedly and reliably.

Orbital Transfer Vehicles (OTVs) based on a solar power source, for example, will probably be required to coast during eclipse periods because the massive batteries required to provide continuous power would not be cost effective. Using batteries to maintain continuous arcjet operation is not an attractive alternative because it would add considerable mass to the satellite, but only reduce the trip time by about 10%. Therefore, in transferring from LEO to GEO, the satellite will experience hundreds of eclipses, subjecting the thrusters to cyclic operation.

Even for missions with constant power availability, such as an SP-100 nuclear power source, the capability for multiple startups and shutdowns will probably be required to accommodate a variety of missions over relatively long durations (7–10 or more years). Although the number of cycles may well be less than that for the solar powered system, small vehicle altitude control or orbital changes could also require the thrusters to cycle several hundred times over the life of the satellite.

While several research efforts are concentrating on the development of both low (3 kWe) and high (30 kWe) power arcjet thrusters for electric propulsion applications, relatively few efforts are addressing the power supply electronics required to operate these thrusters. Experiments on arcjets typically have used large laboratory power supplies which are inappropriate for any space system design. The type of power conditioning unit (PCU) needed for arcjet operation must be capable of controlling the current into the current-voltage characteristic of an arc, where the dynamic resistance has a negative slope. Furthermore, the PCU must operate with high efficiency and reliability in a small, compact, well-designed package that is thermally, mechanically, and electrically compatible with the spacecraft. Another PCU requirement is the capability of starting the arcjet.

HIGH POWER ARCJET PCU DEVELOPMENT

Space Power, Incorporated (SPI) started the research and development of the 30 kWe arcjet PCU in 1986. The original work was funded by Air Force Astronautics Laboratory under the "Arcjet Electronics" program. The first 30 kWe PCU was built during that program and is now referred as PCU I.1.

A second PCU, PCU I.2 was also built during the period between the original contract and this effort.

The third arcjet PCU, the PCU II, was built in this program. This PCU is fundamentally different from the previous ones in both mechanical and thermal design. It does not need forced liquid cooling and is more compatible with a vacuum environment. Therefore, PCU II is much closer to a flight qualified arcjet PCU.

OBJECTIVES

The overall objective of the proposed Phase II program is to develop a long-life, high power arcjet power conditioner with incorporated startup circuitry. This objective will be achieved through selected analysis, computer simulation, design, and verification experiments—including tests in which the PCU is used with representative ammonia propellent, high power arcjets.

DESIGN DETAILS

Several technical issues are discussed in this section. Some of these issues are related, and are presented for one or more of the following purposes.

1. To explain our understanding of the issues.
2. To present our approach.
3. To raise concerns on potential problems.
4. To suggest solution(s) to the issues.

I/O SPECIFICATION

The following is a discussion of the issues concerning the input/output interface of the arcjet PCU.

Input Power

The arcjet PCU was designed to operate with a constant voltage source. The low output impedance of the input source is important because of the high current demanded by the PCU. Additional input capacitors are usually required to minimize the voltage sag at startup. The exact amount of input capacitance is determined by the source impedance, the response of the voltage regulation loop, the distance between the source and the PCU, the requirement of conducted EMI, and the design of the EMI filter.

This PCU was designed for an input voltage of 150–200 V and an arcjet voltage up to 120 V. (The minimum voltage of 150 V may be increased to 170 V if the maximum voltage is higher. Please refer to the section Output Voltage). It is worth noting that, by using higher blocking voltage MOSFETs and slightly bigger inductors, the input voltage range can be increased to allow more battery run down or poorer regulated power if it is determined to be a better trade-off for the whole system.

The PCU also requires low power, low voltage power supplies of ±15 V and +5 V to operate its logic and control circuit. Since the power consumption of this circuit is very low, this power can easily be derived from any standard power source such as 28 V. The power supply of these voltages can also be generated from the main power bus (150–200 V) if a separate logic power bus is not available. PCU II uses an independent power supply to generate the ±15 V and +5 V from the 120 V A.C. line.

Control Signals

The arcjet PCU uses a potentiometer for output current control and a push-button switch for startup signal. This interface was for a stand-alone system that is operated directly by an engineer or technician.

For a flight arcjet systems, these control signals will most likely be initiated from a higher level controller/computer or the ground station. Besides the start signal, other status signals such as temperature, current, and voltage measurements will also be needed to transmit status information back to the controller, computer, or ground station. In this particular PCU design, the "start" command is the only ON/OFF 2-state signal, all others are analog signals. The voltage level and impedance of these control and status signals should be designed to be compatible with the high level controller to which the PCU will be interfaced. Isolated drives may be necessary dependent on the spacecraft architecture.

Electro Magnetic Interference (EMI)

The radiated and conducted EMI generated by the arcjet system could cause problems in the related subsystems or other electronic instruments in the spacecraft. The acceptable level of EMI must be clearly defined to ensure the compatibility among all electronic systems including the arcjet systems.

SPI did not design and build the arcjet PCU II to meet any specific set of the EMI requirements. However, it did attempt to minimize the radiated and conducted EMI for the benefit of the PCU's stable operation. Excessive EMI would create "cross-talk" between the three phases and affect the stability of the output. (Refer to the Duty Cycle Stability Limits section.) The efforts include the use of an SPI proprietary fast recovery rectifier circuit to reduce the EMI generated by the free-wheeling diode and the use of strip-line techniques to reduce the electromagnetic radiation. These efforts were substantially successful in controlling the "cross-talk" between the three phases.

Because extremely high current is switched rapidly inside the arcjet system, it would be very difficult and costly to meet typical military specifications for EMI conformance. A modified EMI specification may be needed for spacecraft with a very high power arcjet system.

Output Characteristics

Constant Current Source

The arcjet PCUs are best described as a constant current source. It has a very high output impedance.

The third arcjet power conditioning unit, PCU II, was designed to operate in constant arcjet current mode only. There may be a need to operate the arcjet PCU in a constant power mode. PCU II could be converted to a dual mode PCU without much difficulty, because the constant power servo loop is a very slow outside loop that senses the arcjet voltage and makes adjustment to the current reference level to maintain a constant arcjet power. Since the time constant of the constant power loop is on the order of several seconds or longer, this function could also be performed by the high level computer.

Voltage Range

The original operating range of the arcjet PCU was 70–120 V. The voltage of the arcjet depends on the design of the thruster. When SPI prepared the specifications for this arcjet PCU, JPL operated 30 kWe arcjets at around 110–120 V while RRC operated them at around 90–100 V. As the project progressed on, higher and higher arcjet voltages were proposed. Operating voltages as high as 130–135 V have also been mentioned.

PCU II is able to operate the arcjet up to 135 V, or even somewhat higher voltage, provided that the input voltage is at least 20–25% higher than the output voltage. The reason for this was described in the Duty Cycle Limitation section. For example, if the arcjet voltage is 135 V, PCU II will need a minimum input voltage of 165 V. Meanwhile, the PCU is only designed for 200 V maximum input voltage. Under this situation, the voltage range for battery run-down is limited to 35 V (200 minus 165 V). This small range of battery rundown may increase the size of the battery. A possible solution is to increase the upper limit of the input voltage. The 200 V maximum input voltage can be increased by redesigning some of the components in the PCU. This may result in increasing weight and size of the PCU. A more detailed trade study is required to define the optimal bus voltage requirements. However, SPI did not recommend spending a significant effort optimizing the design until the useful arcjet operating voltage range is clearly defined.

Output Current

Output current is controlled by a current control reference signal, which is selectable from a potentiometer mounted on the front panel. PCU II should be able to handle a very wide range of output current as long as the output voltage is within the design limits. From the PCU point of view, the output current can be set anywhere between 30–300 A. However, the amplitude of the current ripple is a function of output inductance, switching frequency and output voltage. It will not vary with the average arcjet current, Therefore, the percentage of arcjet current ripple will be increased if the average arcjet current is lower. Other than the high percentage ripple at low current operation, the PCU is capable of operating the arcjet thruster over a very wide range of power levels.

TRANSFORMER ISOLATION

This arcjet PCU uses a simple buck regulator topology. There is no step-up or step-down transformer to isolate the output power from the input power. In other words, the input terminals and output terminals must share a common return. This poses a restriction on the grounding of the power sources and the arcjet thrusters. For the convenience of the propellant feed system, it is usually desirable to connect the anode of the arcjet thruster to the spacecraft chassis ground because the anode connects to the propellant feed system directly. With a non-isolated PCU and a grounded anode system, SPI can only use the power source with a positive ground or a completely floating power source to power the arcjet system. Therefore, the decision of whether to use an isolation transformer should be made at the spacecraft level.

A non-isolated PCU has higher efficiency along with many other advantages except the restrictions of grounding. However, in many cases, the arcjet system is probably the largest power consumer in the spacecraft. A Trade Study should be performed for each individual situation to determine whether it is wise to allow the arcjet system to dictate the system grounding configuration to optimize the overall efficiency.

A meeting was held at JPL in December of 1988 to discuss this issue. No decision was made at that meeting. Since then, SPI has discussed it with Albert Chung of G.E. who was working in the SP-100 electrical system, and other people in the arcjet community. SPI was not able to draw a conclusion because the SP-100 electrical system had not been defined detailed enough to answer this question.

The following is a summary of the benefits of a transformer-isolated PCU.

1. To reduce interference to other equipment.
2. To allow more flexibility in grounding arrangement of the arcjet and its propellant feed system.
3. To remove the restriction on the range of input voltage to the PCU.

The following are the benefits of a non-isolated design.

1. Existing design and proven performance.
2. Simplest approach—higher efficiency, higher reliability and lower mass.

The final decision for using the non-isolated approach in this program was made after SPI was informed that JPL people involved in the SP-100 program had a meeting about the isolation issue and had concluded that the non-isolated approach is more desirable for SP-100. The plan was to use a non-isolated simple buck regulator type arcjet PCU and to let either the cathode or the anode connect to one end of the power source. The propellant feed system will also be floating. This was a less risky approach because SPI had already built two PCUs of this type and had demonstrated proper and stable operation with a 30 kWe ammonia arcjet. More discussion of the grounding issue can be found in Appendix A.

DUTY CYCLE LIMITATION[1]

Need For Current Transformers

SPI needs to measure the output (inductor) current of each phase in the PCU for two purposes. The first purpose is for the input of the servo-control loop that regulates the average arcjet current. The second purpose is for the input of the comparator that directly controls the turn-off timing of the power switches in each cycle. The later one requires a very clean signal because it controls the output directly and any noise will cause fluctuations in arcjet current. (See also the Duty Cycle Fluctuation section.)

A common technique to measure current is to use a shunt resistor. The arcjet PCU is a low voltage and high current system. The current shunt technique was not suitable for the arcjet PCU because there is a dilemma between getting a good signal to noise ratio and holding the loss in the shunt resistors low. For example, if a 1 V full scale signal for 100 A is wanted, the power loss in the shunt resistor alone will be 100 W or 1% of total power. This loss is intolerable because the total allowable loss in the arcjet PCU is only 3–4%. Reducing the resistance of the shunt will result in a poor signal to noise ratio. Therefore, the current transformer approach was chosen to allow flexibility in manipulating the signal to noise ratio without the constraint of the system efficiency.

The major hurdle in using a current transformer to measure the output current is the fact that output current is a direct current rather than alternating current. If a regular current transformer were to be used, only the a.c. component of the inductor (arcjet) current could be sensed at the output (secondary winding) of the current transformer. Therefore, a simple current transformer cannot be used for this purpose. SPI used an alternate approach that has the benefit of the regular current transformer (high signal to noise ratio and low power loss) and is able to measure the d.c. component of the arcjet current.

As shown in Figure 1, the output current I_l is the same as the inductor current, which is the sum of the diode current and the switch current. The waveforms of I_l, I_d, I_s are shown in Figure 2. Although it is impossible to measure the I_l by a current transformer, both I_d and I_s can be measured by the a.c. polarized current transformer because both of them go back to zero in every cycle. This unique characteristic allows us to extract the d.c. measurement during the on time and reset the transformer core during the off time. An operational amplifier is used to synthesize the I_l by summing the T_d and the I_s together.

However, there was a drawback in using a current transformer. The current transformer technique required a minimum period in each cycle to allow the flux of the transformer core to be reset. This limits the maximum duration in each cycle that the current transformer can be used to measure the current. In other words, there was a limit on the duty cycle that the PCU could operate. If the PCU exceeded the limit, the flux in the cores of the current transformers were not completely re-set in each cycle. The output signal of the current transformer would be lower than the actual value. This false measurement would mislead the control circuit, and make the PCU increase the output current and eventually run out of control. Therefore, SPI incorporated a safety circuit in the PCUs to shut themselves down before the run-away could occur. The threshold of the shut down circuit determined the maximum operating duty cycle of the PCU.

The operating range could be widened (increase the maximum duty cycle) of the PCU by tuning the value of some components in the current transformer reset circuit. However, there was a trade-off in the design. If the operation range is pushed to exceed a certain limit, the measurement of the transformer would have a erroneous d.c. offset that adversely affected the accuracy of the current measurement and degraded the arcjet current regulation. In other words, the accuracy

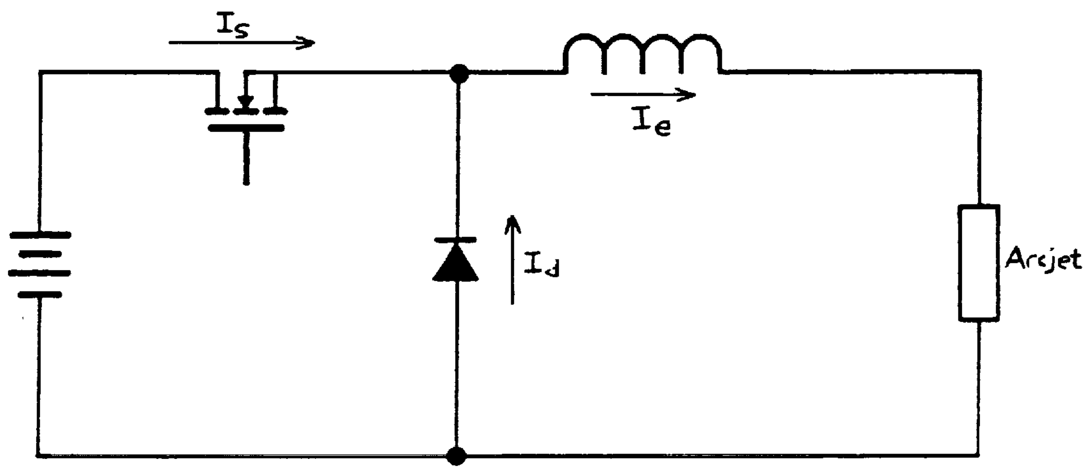


Figure 1. Buck Regulator Current Path

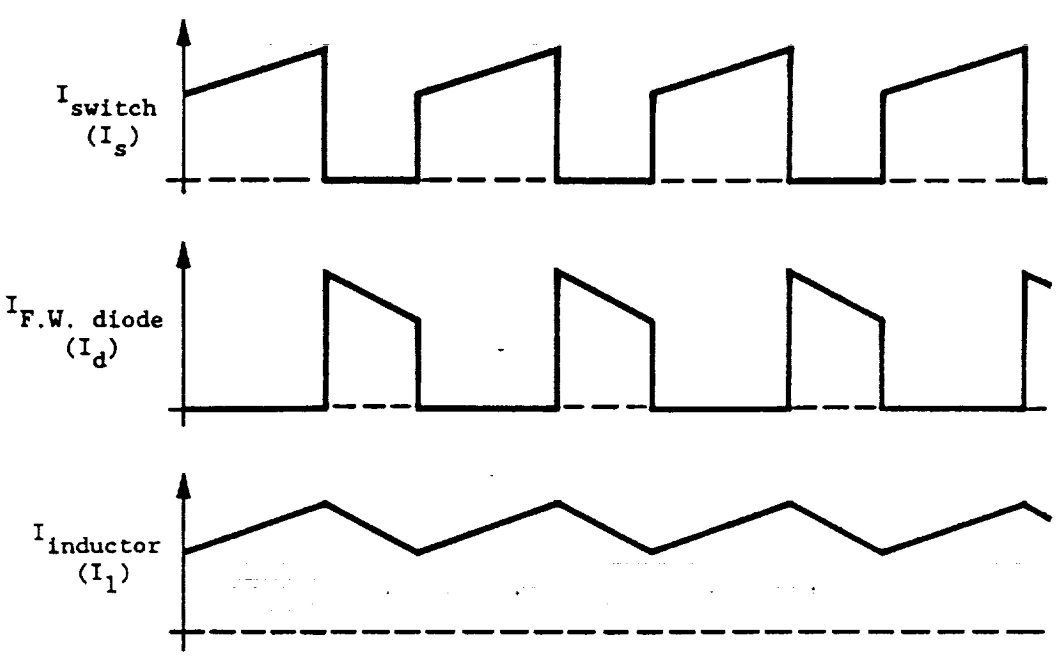


Figure 2. Buck Regulator Current Waveform

of the current regulation and the range of the operating duty cycle pose two interrelated constrains in the circuit design.

The PCU was originally designed for a minimum input voltage of 150 V and a maximum output voltage of 110 V. With this operating range,there was no need to operate the PCU above 75%, and there was no difficulty in duty cycle limitation encountered. Unfortunately, the expected voltage of the arcjet was later increased to 120 V or even higher. The above-mentioned constraint became a potential problem. The PCU II was tuned to operate up to 125 V with minimum 150 V input. It could operate arcjets at a higher voltage if the input voltage was proportionally higher. There was a slight compromise in the output regulation. With this compromise, the output current changes <4% over the input range of 150 V to 190 V.

If there is enough difference between the maximum output voltage and the minimum input voltage, this duty cycle limitation will not be a concern. For example, if the maximum arcjet voltage is about 130 V, an input voltage ranging from 165 V to 200 V will be adequate for the arcjet system.

There were several techniques to remove the restriction of the duty cycle such as using shunt resistors rather than current transformers, using two alternating switches per phase to limit the duty cycle for each switch to 50%, or developing a more complicated flux reset circuit to further reduce the minimum off time requirement. SPI did not think that it was an urgent need for the arcjet PCU. If one wanted a PCU to operate with wide range of input voltages, the transformer isolation design was probably the better choice because it could also provide a step-up or step-down ratio to match the input voltage range. Furthermore, the maximum arcjet operating voltage is still a moving target.

DUTY CYCLE STABILITY LIMITS

The arcjet PCU is a current-mode control buck regulator. The output current is being regulated by the duty cycle of the power switches. Current-mode control is a first order system which is intrinsically free of second order oscillation. However, SPI has still experienced output fluctuation problem during high power operation. The fluctuation, which has nothing to do with loop stability, was caused by the switching noise occurring at 66.67%, or two thirds, duty cycle.

In order to discuss the cause of the duty cycle fluctuation, we need to revisit the circuit topology of the arcjet PCU. The PCU consists of three independent buck regulators, referred to as the three phases. Each phase includes its own power switch, free-wheel diode assembly and output inductor. Switches of the three phases are fired at 120° out of phase. The current ripple of each phase is largely cancelled out by the other two phases. Therefore, the resultant ripple of the arcjet current is significantly lower than the ripple of each individual phase.

In each phase, the duty cycle of the switch is controlled by a current mode pulse width modulation controller. A comparator is used to compare the current of the power switch to a reference level. Switches are turned on at the beginning of every cycle and turned off when the comparator outputs flip as they sense the current of the power switches exceeding the reference level. This reference level moves up or down by the servo loop to regulate the average value of the arcjet current.

Fluctuation in duty cycle occurs when there is noise in the waveform of the switch current measurement. This noise will give a false alarm to the comparator and makes its output flip prematurely. This effect is most predominant if the noise happens when the switch current measurement is very close to the reference level, because, at that moment, even a small noise is enough to trigger the comparator. This situation occurs at about two thirds duty cycle at which the switch in one phase turns on just before a switch of another phase is supposed to turn off.

The premature turn-off of the power switch shortens the duty cycle of that particular cycle. The power switches will stay "on" longer in the following cycle to make up the missing "on" time so that the average arcjet current will remain the same. This fluctuation of the duty cycle will result in a higher than normal random ripple in arcjet current and voltage.

The amplitude of the duty cycle fluctuation is about 1 μsec out of a 50 μsec period. Because this occurs at two thirds duty cycle at which the steady state ripple is at its minimum, the total resultant ripple, including the random ripple from duty cycle fluctuation, is still lower than the maximum steady state ripple at 50% duty cycle, at which the steady state ripple is at its maximum.

In several occasions, the random ripple introduced by the duty cycle fluctuation was quite significant. They were caused by various reasons such as a loose ground connection, broken shielding, or even a damaged rectifier. The fluctuation became a common symptom for many non-fatal component or subsystem failures.

Therefore, it is not easy to pinpoint the source with this symptom alone.

There was no evidence that the fluctuation itself had caused or been directly related to any system failure. However, it was annoying to watch the voltage and current waveforms with fluctuations in the duty cycle. Therefore, it is desirable to de-sensitized the circuit so that the PCU is not as susceptible to noise interference. An opto-coupler could reduce the interference. However, space system designers always want to avoid the use of opto-couplers in space. Using transformer isolation is another possibility. It is not clear that this worth the trouble of providing many floating power supplies. How to minimize the interference among the three phases is an issue that requires more study.

ARCJET START-UP

There are two steps in starting an arcjet. The first step is to introduce a gaseous breakdown in the propellant. The second step is to deliver current fast enough that discharge will be maintained and to deliver the current in a well controlled fashion that is free of excessive surge current.

Methods

In order to start the arcjet, a mechanism to induce the propellant breakdown was needed. There are several different ways of starting an arcjet in the laboratory environment. Some methods previously used were:

1. Starting with argon and switching to another propellant after the thruster is warmed up.
2. Using a fine fuse wire to breakdown the propellant.
3. Charging up a high voltage capacitor across the electrodes of the thrusters until the arc starts. A rectifier is used to decouple (block) the high voltage from the PCU.
4. Introducing a high voltage pulse through a secondary winding in the output inductor.

All the above mentioned methods will start arcjets. Some procedures are more difficult and some are more distructive. This report will not discuss these methods in detail because most of them are not suitable for space applications. Method 4 is the only one that has the potential to be used in a space environment. This method is being developed and used for the low power arcjet PCU.[2] SPI selected an approach that is similar to this method and is also suitable for space applications. A starter circuit using this approach was built in Phase I of this program and the feasibility had already been demonstrated. This approach is to turn on a shorting switch across the output terminals of the PCU (the electrodes of the arcjet thruster) to develop current in the output inductors. The shorting switch will then be turned off abruptly to create a flyback high voltage pulse across the arcjet thruster (output of the PCU).

Trade Study

SPI believes the shorting switch is a better approach for the high power arcjet PCU. Some concern has been raised about the use of a high voltage switch across the output. The start winding approach can take advantage of the turns ratio to avoid the use of a high voltage switch by switching a winding that has a lesser number of turns. However, due to the conservation of energy, lower voltage switching is always accompanied by higher current switching of the same ratio. For low power systems, this may be an attractive trade-off. The benefit of avoiding high voltage switching by switching high current is questionable when the current becomes as high as 1000 Amps. A trade study to compare the pros and cons of these two approaches was performed and the results of this trade study are shown in Table 1. Based on the result of the trade study, SPI recommends the shorting switch approach for the starter circuit of the high power arcjet PCU.

Start Voltage

One important parameter of the starter circuit is the amplitude of the output voltage pulse that is needed to start the arcjet. NASA LeRC had studied the ignition of low power arcjets.[2] There are no existing data in 30 kW-class arcjets to determine the minimum voltage that is sufficient to consistently start an arcjet. Under certain conditions, high power ammonia arcjets have been started as low as 700–800 V D.C. Because the arcjet starter will generate a narrow pulse rather than D.C., an early speculation on the short duration pulse voltage required to start the arcjet is about 1000–1500 V. Based on this speculation, SPI set the design goal at 2000 V and felt that this would be conservative enough to cover the variations of thrusters. This is why the start circuit of the arcjet PCU generates a high voltage pulse of >~2000 V.

During the same period of this program, a low power arcjet development effort has been carried on by a group of organizations including NASA LeRC and RRC. Test data from that effect's low power arcjet test-

Table 1. Comparison of the Two Approaches to the Starter Circuit.

	Start-Up Winding	Shorting Switch	Discussion
Switch Requirement	Low voltage, high current	High voltage, high current	The switch(es) used in the shorting switch approach need to block ~2000 V of start voltage directly. The switch(es) used in the start-up winding can be arranged to switch at a lower voltage at the cost of switching higher current by manipulating the turns ratio of the start-up winding to the inductor winding.
Additional Winding	1 or 3	0	A minimium of one set of additional windings is required in the start-up winding approach. However, if only one set is used, the two inductors that do not have start-up winding will serve as unwanted current paths which will reduce the impedence at the output terminal, thus the amplitude of the high voltage. Furthermore, even after the arc is ignited, the reverse current in the two passive inductors may adversely affect the chance of sustaining the arc. In our opinion, if the start-up winding approach is selected, using three sets of start-up windings is more desirable.
Stored Energy	Higher	Lower	Assuming the same amount of energy is required to charge up the capacitance between the cathode and the anode of the arcjet thruster, and the connecting cables. The energy stored in the inductor(s) of the start-up winding approach will be higher due to the coupling loss of the start-up winding. The coupling coefficient of a heavily gapped core will not be very high. This means the power switches are required to switch more energy.
Simplicity	More complicated	Simpler	The start-up winding approach is more complicated because it requires at least one additional winding (preferably 3) and it has to switch higher energy.
Size and Mass	Bigger and heavier	smaller and lighter	The start-up winding approach will add some additional weight to the PCU because of additional winding(s). The difference is probably insignificant.

ing indicate the voltage requirement of the start pulse may be higher than the expectations. In some instances, high voltage pulses as high as 3500 V were required to start the arcjet.[3] The physical dimensions of the low power arcjet thruster and the high power arcjet thruster are quite different. It is not easy to infer the voltage requirement of one design based on the test results of the other. Nevertheless, these results suggested that the start voltage required for the high power arcjet may be higher than our initial expectations. At the time that this report is being written, several start tests have been performed with this high power arcjet PCU with the built-in starter. The starting voltage is 2100 V ±100 V. The pulse duration is about 500 nsec. This pulse can start both ammonia arcjets and hydrogen arcjets under some circumstances. For more detailed information, please refer to the Test Data section of this report. The following is a summary of our arcjet starting experience.

Hydrogen arcjet: Started at each of several attempts at 0.25mg/sec. Slight reduction of propellant mass flow rate made the start-up much easier.

Ammonia arcjet: Started the thruster easily for a wider range of mass flow rate in most cases. Experienced more difficulty with a thruster that has been stored for many months. The same thruster became easy to start after a brief operation. Reducing mass flow rate made starting easier also.

Surge Current

After the propellant has been broken down, current will begin to flow through the thruster. The initial current could be quite high. The amplitude of the initial surge current depends on the control loop response of the arcjet PCU or the laboratory power supply used to operate the arcjet. In some cases, an initial surge current as high as 1000 A was observed when the 30 kWe arcjet was tested with a laboratory power supply.[3] When the arcjet PCU I.1 was first tested at RRC, the initial surge was ~700 A. This high surge current has a detrimental effect on the cathode degradation. Therefore, part of the effort in this program is to minimize the amplitude and duration of the surge current.

The arcjet PCU is a constant current power supply. The arcjet current is regulated by a servo-control loop. The presence of the startup surge current is due to the limited response bandwidth of the servo loop. Before the arcjet was started, the integrator output of the servo loop had been driven to saturation. The control loop would turn the switch on at the maximum allowable duty cycle in an attempt to increase the current. Once the arcjet was started and the control loop began to sense the arcjet current, the integrator would start recovering from the saturation. Until the integrator was completely recovered, the output current would go beyond the set level and constitute the surge current. Therefore, the amplitude and the duration of the surge current are dependent on the response time of the servo loop.

SPI could use two approaches to minimize the surge current. The first one is to speed up the response time of the servo loop so that the integrator will recover sooner. The second one is to put more restriction on the hardware limit of the saturation voltage so that surge current is limited to a lower level even when the integrator is saturated. SPI took both approaches and had achieved significant reduction in both the amplitude and the duration of the surge current. Figure 3 shows the waveform of the surge current when the PCU was tested with arcjet thruster at RRC before the circuit improvement. Figure 4 shows the waveform after the improvement.

Soft-Start

The anode of the thruster is made of a large piece of solid metal. If the arcjet current goes from zero to a high value abruptly, a large amount of heat will dissipate in the arcjet anode. Since the heat is only applied to the inner surface of the thruster, it will create a large temperature gradient between the inner and the outer surfaces of the anode. This large temperature gradient may cause cracking in the anode. In order to prevent anode damage caused by thermal shock, the arcjet should go through a gradual warm-up period. During the warm-up period, the arcjet starts at a relatively low power level and then will be raised gradually to full power. This mechanism is called the "soft-start".

Surge Current Versus Soft-Start

Although both the soft-start and the surge current reduction are aimed at minimizing the damage at startup, they are clearly distinct subjects and require different treatments. The duration of the surge current is in the order of microseconds and the timing of the soft-start output control is in the order of seconds. The approaches to improve them are completely unrelated. To minimize the surge current, SPI needed to optimize the performance of loop response. To implement the soft-start for warm-up, SPI added an additional timing circuit to control the rise of the reference signal for output current.

The soft-start function was not part of the original PCU design. Nevertheless, the output current is servo-controlled to follow a reference signal. For example, the signal for constant arcjet current is a constant D.C. level. SPI achieved the soft-start function by manipulating the reference signal. Either an operator or an external controller/computer could set the reference signal low at the beginning and raise it gradually to achieve the soft-start effect.

In order to minimize the cost impact of incorporating a soft-start circuit in this PCU, a very simple approach was used. SPI does not recommend the same approach for the flight unit because of its limited flexibility. However, this simple approach will be able to provide the basic function of the soft-start. The approach is to rapidly pull down the reference signal for the arcjet current before the start pulse and to let it go back up slowly to its steady state level after start-up. The rate of rise of the reference signal after start-up depends on a timing capacitor and the impedance of the charging current. In this way, the time constant of the soft-start function was easily adjustable by the timing capacitor. A multi-position switch was used to select among several capacitors so that the time constant could be set on the front panel. Originally, the time constant of the soft-start circuit included ~200s, ~20s, ~2s, ~200ms. The waveforms of the soft-start circuit are shown in Figures 5 and 6. These waveforms show the PCU output current when it was tested with an arcjet simulator.

When the PCU was tested at NASA LeRC, the soft-start circuit caused some unexpected complications. SPI was not able to start the arcjet with the PCU's build-in starter when it was first tested with a hydrogen arcjet. The hypothesis was that the soft-start circuit could cause the arcjet to go off even after it was started by the high voltage pulse because the soft-start circuit might have forced the initial arcjet current so low that the arcjet voltage exceeded the PCU operating range. This hypothesis was later confirmed. SPI was able to start the arcjet after the time constant was reduced to about 20ms.

Even though SPI had difficulty in starting the arcjet with the soft-start circuit, there is no intention of eliminating the soft-start function. More care must be taken with the initial current level to make sure it will not be too low to create a voltage over-range problem.

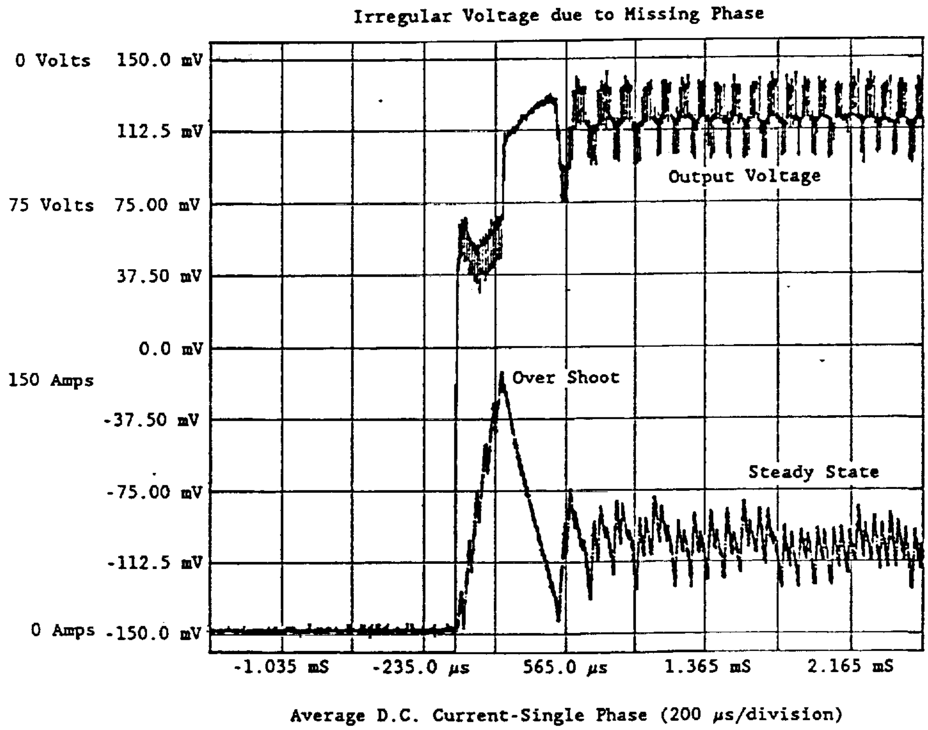
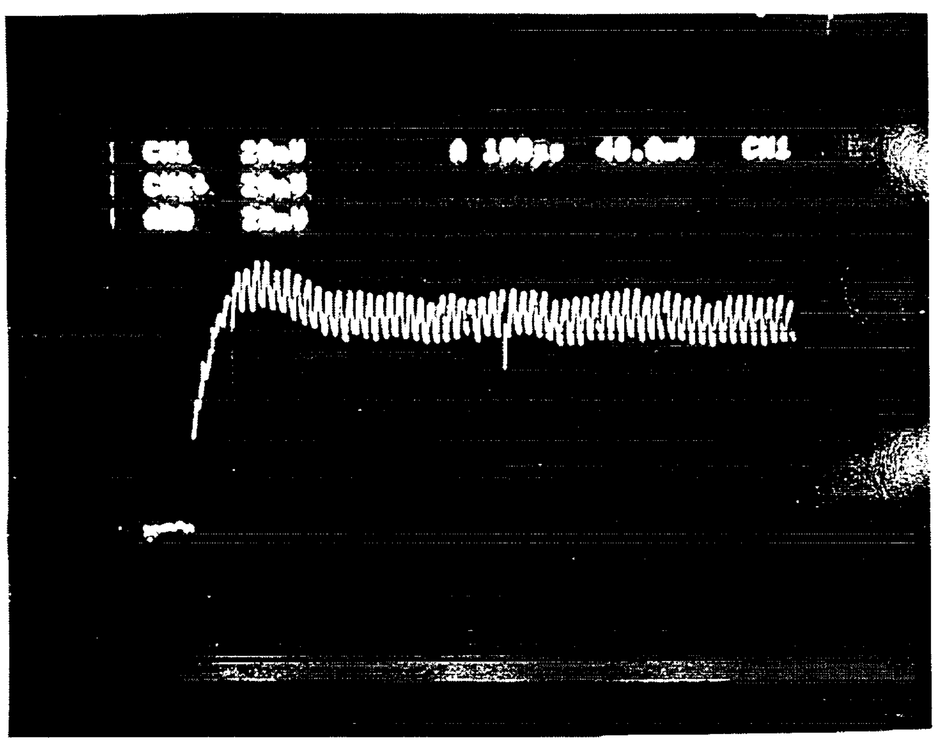


Figure 3. Voltage and Current Waveform at Start-up



40 Amp Per Division

Figure 4. Start-up Current Waveform

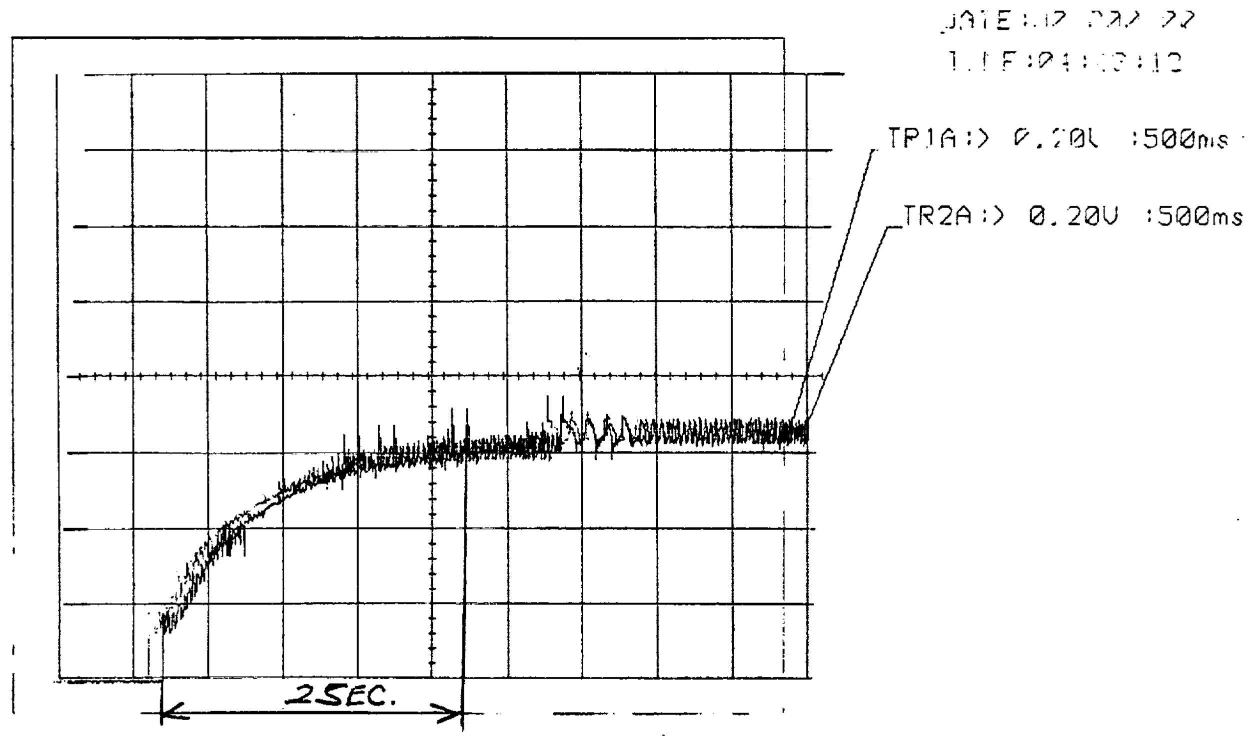


Figure 5. Soft-start Circuit Waveform

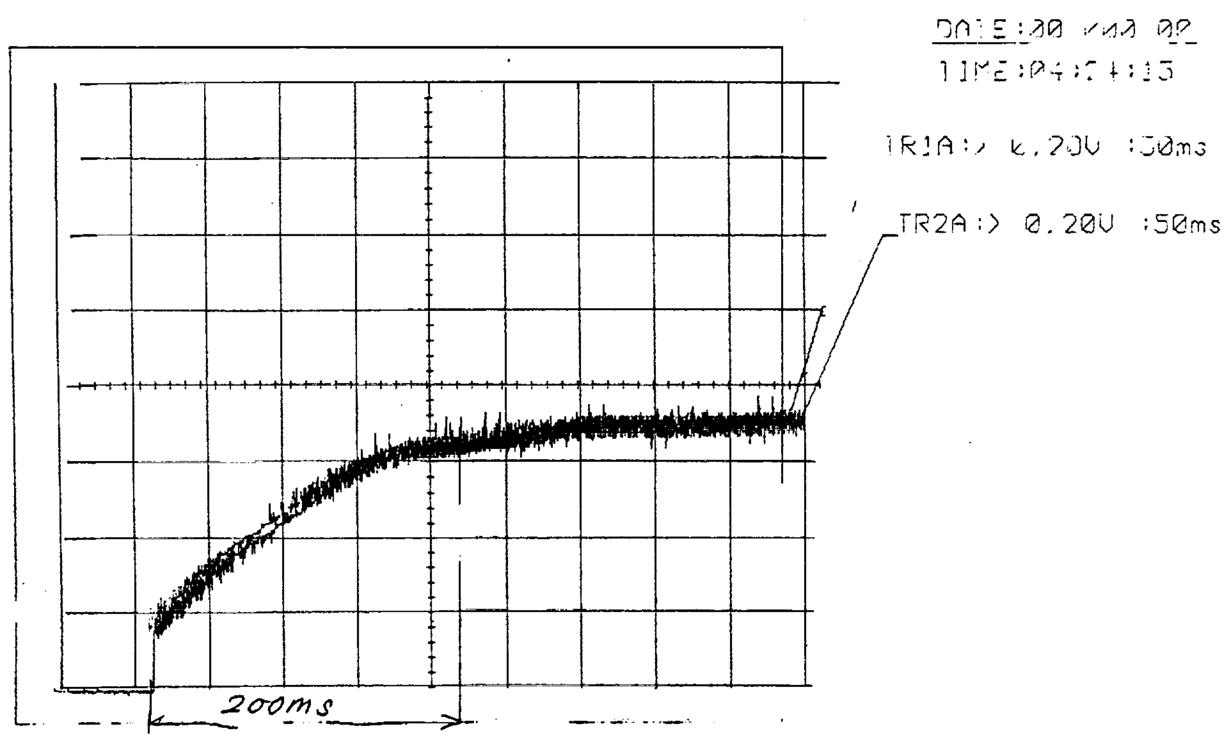


Figure 6. Soft-start Circuit Waveform

Soft-Start Function Placement

As mentioned above, the soft-start function has a very long time constant. Fast response is not required. Therefore, depending on the system architecture, it may be better served by the higher level controller/computer. If this function is performed by the PCU, SPI recommends using a more flexible circuit than the one used in this PCU. A digital counter with a D/A converter can generate a precise ramp for a wide range of time constants. If necessary, this arrangement can control the arcjet current to follow any arbitrary waveform that is input from a remote controller or stored in a programmable read only memory (PROM).

SHORT CIRCUIT PROTECTION

A reliable PCU should be able to handle any load without risk of damage. High risks are always associated with extreme cases. The two extreme cases for loads are open circuits and short circuits. Open circuits will usually create high voltages that could damage sensitive components. In this particular PCU design, SPI used the fast open circuit to create a high voltage pulse to initiate an arc or start the arcjet. The PCU is well prepared to handle the sudden open circuit reliably. Therefore, an open circuit is not a problem. On the other hand, short circuits usually create a high surge current. The PCU is a constant current source. Ideally, it is designed to regulate the output current regardless of the load and short circuits should not damage the PCU. However, this statement is only true for steady state operation. The PCU requires a finite time to respond to a sudden load change. When the load resistance changes abruptly while operating at high power, the output current will surge momentarily before it recovers. Depending on the amplitude of the surge current and the recovery time, it could cause irreversible damage to the PCU. The effort of improving the short circuit protection was to minimize the amplitude and duration of the surge current so that sudden short circuits caused by contact of foreign objects or breakdown of non-critical components will not pose a severe threat to the health of the PCU.

SPI paid special attention to the short circuit problem after the PCU was damaged by an output short circuit, caused by incorrect grounding in an arcjet system. After that, SPI has carried out a thorough examination of the short circuit response of the arcjet PCU and have modified the control circuit to greatly improve the response. Because both the short circuit protection and the surge current control are related to the response of the loop, many of the efforts were beneficial to both concerns.

The best way to determine the response and the performance of the short circuit protection circuit is to observe the output current waveform while shorting the output terminals together. Figure 7 shows this current waveform. The surge current in the early design was as high as 500 A and lasted several msec. Initially, this high surge current at short circuit caused excessive stress to the power MOSFETs. One of the power transistors in the arcjet PCU was permanently damaged during short circuit testing. The current waveform at the moment of failure is shown in Figure 8.

Two approaches were used to minimize the potential damage of the surge current at short circuit. The first one was to speed up the response time of the current control loop. This would reduce the pulse width of the output surge current. The second one was to reduce the amplitude of the surge current. This was done by adjusting the slope compensation used in the current-mode PWM control. The result of these two efforts was very successful and greatly reduced the stress to the power MOSFETs at short circuit. Figures 7 and 9 show the current waveforms before and after the circuit improvement was implemented. These figures have the same horizontal and vertical scales. Therefore, it is easy to see the significance of the improvement.

EFFICIENCY

Waste heat rejection is a serious issue in high power arcjet systems. Waste heat generated by the arcjet PCU must to be rejected to space through radiator panels. It is important to have a high efficiency system to keep the size of the radiator panels manageable.

The efficiency goal of this arcjet PCU was 95%. Based on previous experience, SPI was confident of achieving this goal. The efficiency measurements of the previous arcjet PCUs were on the order of 94–95%. SPI anticipated the efficiency of this PCU to be somewhat higher than the previous ones. The key difference is the increase in number of MOSFETs used in the PCUs. The new PCU used twice as many as MOSFETs as were used in the previous PCUs. Therefore, the conduction loss of the MOSFET switches should roughly be reduced by half. (Switching loss of the MOSFETs would not change significantly or even be somewhat higher due to the slower switching). Table 2 shows an itemized estimation of loss in the arcjet PCU.

This table shows the percentage estimated loss of each component that dissipates significant power. The estimate is approximate because:

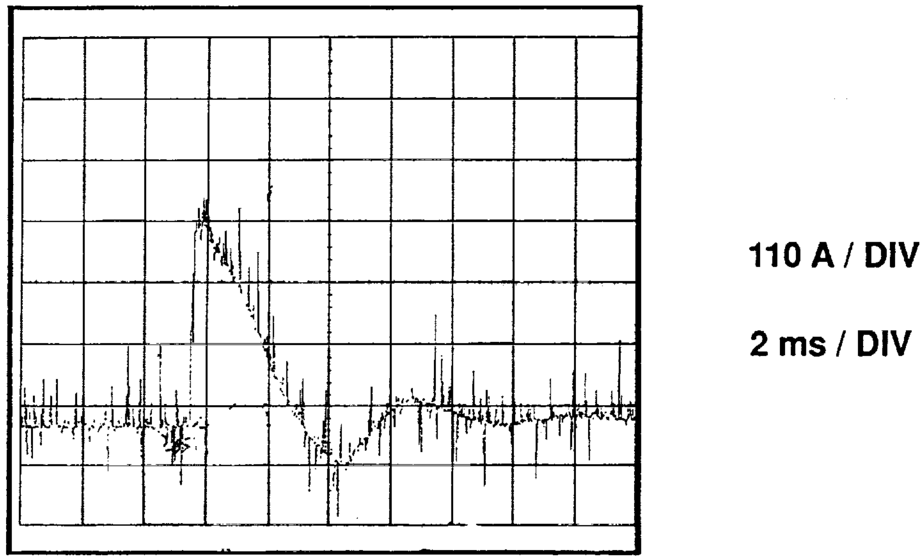


Figure 7. Short Circuit Response Before Improvement

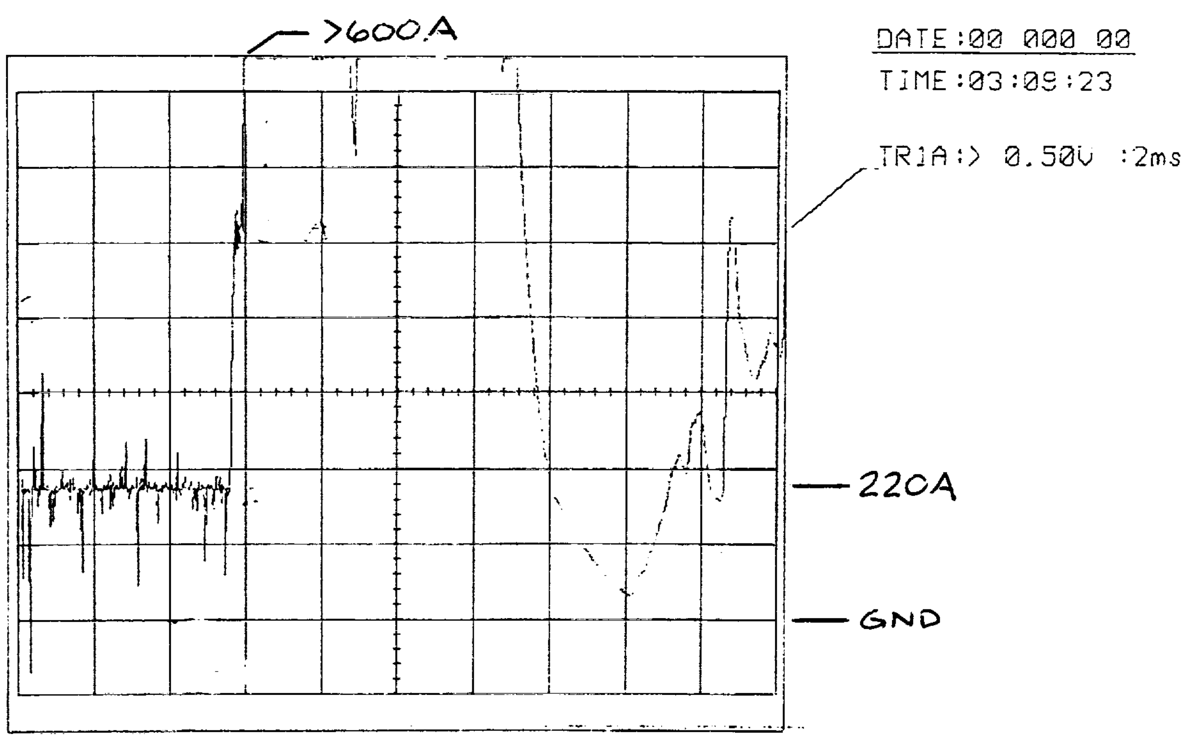


Figure 8. Current Waveform at Failure

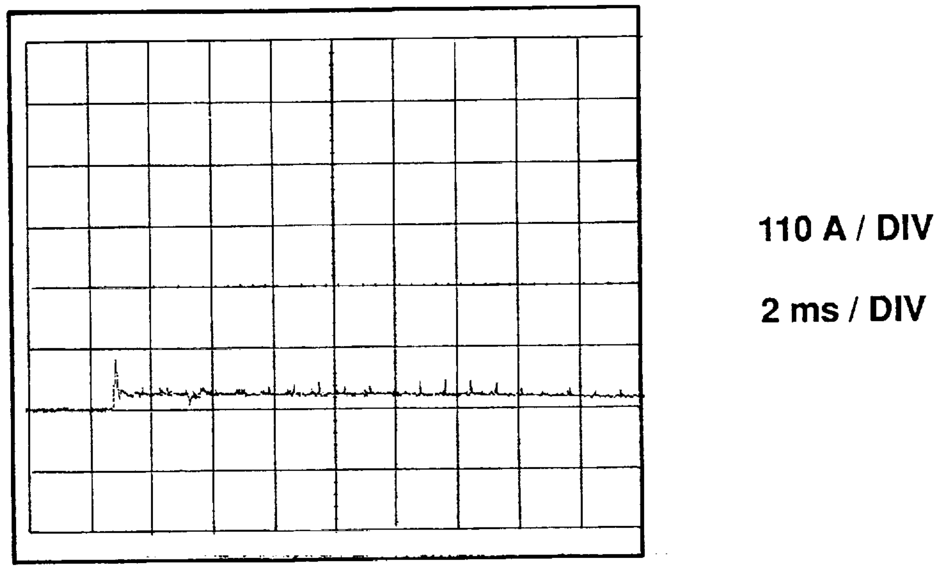


Figure 9. Short Circuit Response After Improvement

Table 2. Itemized Estimation of Loss as a Percentage of Total Loss

Component		Percentage of Total Loss	
Switches	Conduction Loss	30%	
	Switching Loss	10%	
	Total Switch Losses		40%
Snubbers			10%
Rectifiers	Main Rectifier Loss	20%	
	Auxiliary Rectifier Loss	10%	
	Total Rectifier Losses		30%
Inductors			10%
Misc. (Including connectors and conductors)		10%	
Total System Loss			100%

1. The exact loss of each component is dependent on the operating conditions, such as input voltage, output current and voltage, and temperature of each component.

2. The losses of each component are very difficult to measure. Therefore estimates are based on first order approximations.

THERMAL MANAGEMENT

When the PCU operates in space, the most convenient and usually available means of cooling still air conduction and convection-are not available. Therefore, a well-thoughtout thermal design is very important to the successful operation of the arcjet PCU. Heat rejection paths must be provided to every component that generates any appreciable amount of heat. (This is why keeping the efficiency high is so important).

Two basic approaches of thermal management have been developed. The first one is to use forced liquid circulation. This approach was used in the first two high power arcjet PCUs (PCU I.1 and PCU I.2). The advantage of this approach is the flexibility of packaging because coolant can be channeled to any location. Electronic components can be packed tightly together. Therefore, this will result in a smaller and lighter arcjet PCU. The disadvantage of this approach is the requirement of a pump. Spacecraft designers have tried hard to avoid or minimize the use of mechanical components in spacecraft. Of course, liquid metal can be forced to circulate by an electromagnetic pump (EM pump) without moving mechanical parts. However, this will add complication to the spacecraft design.

The second approach is not to use any liquid circulation but rely solely on thermal conduction of the mechanical structure itself. Waste heat generated by the PCU is rejected to the spacecraft through the mounting plate of the PCU. This approach requires a very careful mechanical layout because adequate heat paths must be provided to all heat generating components.

The problem of heat removal from the mounting plate to the radiator panel will be left to the spacecraft designers. They could use forced liquid cooling, heat pipes, or phase change heat reservoirs to remove heat from and maintain the interface temperature of the mounting plate. A PCU with this thermal management is more flexible, because it could easily be adapted to spacecraft with different types of thermal management techniques. The tradeoff is that a PCU with this design will be somewhat bigger and heavier.

SPI decided to use the second approach of no forced liquid cooling in this arcjet PCU program because:

1. SPI had already built two arcjet PCUs using forced liquid cooling. SPI felt it could learn more from taking a different approach.
2. SPI identified that the near-term mission for the arcjet PCU was the Arcjet ATD program. The Arcjet ATD program will not have forced liquid cooling. SPI preferred to develop a PCU that could benefit the future development.
3. The design is more flexible and will be compatible with more spacecrafts.

RESULTS AND DISCUSSION

The test data is divided into two sections. The first section is the data that SPI collected during the in-house testings. The second section is the test data that was collected or obtained from test partners while the PCU was tested with arcjet thrusters in government facilities.

IN-HOUSE TESTING

All the in-house test data were taken with a resistive dummy load. SPI used two different dummy loads in this program. The first one is made with a small ni-chrome wire immersed in a pail of running water. SPI deserted this load because it had a relatively short life and used a large amount of city water. Figures 10 and 11 show this load. The second dummy load is a parallel group of many long strips of ni-chrome wires mounting on a steel and fiberglass rack. Because this load dissipated heat over a large volume at lower temperature, water cooling is not needed. Figures 12 and 13 show this load. Although these two loads are different in size and shape, SPI observe no significant difference in characteristics when they were used in testing the arcjet PCU.

The in-house test data were concentrated in the component and subsystem performance, efficiency measurement, startup and steady state transition, amplitude of output ripples, and output short circuit protection.

The Efficiency Measurement

SPI measured the input and output voltage by a digital multi-meter directly. SPI measured the input and output current by two precision shunt resistors. The shunt resistors were rated for 400 A (100 mV) and 20 A (100 mV). Their tolerances are both ±0.25 %. SPI deliberately used a 20 A shunt to measure the 300 A output current so that there was a large voltage drop across the shunt. The high amplitude of the measurement was needed for observation of the current startup waveform in the noisy environment. The 20 A shunt was completely immersed in a water cooled container to prevent overheating. In order to have a more precise efficiency measurement, the two shunt resistors were cross calibrated with each other and the measurements were adjusted accordingly. All voltage and current measurements were made with the same digital multi-meter. The meter is a high stability, 6½ digit, Hewlett Packard 3456A. This meter is equipped with true rms AC mode. However, to avoid the error caused by the switching noise in the signals, all measurements were made with the average DC mode.

Figure 14 shows the input current shunt. Figure 15 shows the digital voltmeter that was used for all efficiency measurements. Figure 16 shows the multi-position switch that connected all measurements to a single meter. Figure 17 shows the water-cooled shunt for output current measurement. Figure 18 shows the efficiency measurement setup. Tables 3 and 4 show the result of the measurement. Most of the measured efficiencies were about 96 %. Some measurements were even above 97 %.

Inductor Loss Measurement

Because the inductor is a highly non-linear device, the calculation of inductor loss is only a rough estimate. Therefore, SPI decided to measure the total inductor loss at a typical operating condition to cross check the design calculation.

Based on calculations and the core manufacturer's data sheets, the total inductor loss is itemized as follows:

Core loss	=	16.8 W
Copper loss	=	16.3 W
Gap loss	=	12.0 W
Total Loss	=	45.1 W

SPI measured the total loss of the inductor by immersing the inductor into a thermally isolated bucket of oil and measuring the temperature rise of the oil to determine the power dissipated by the inductor.

Mass of oil	= 2.65 kg
Specific heat of the oil	= 0.444 kcal/kg°C
Mass of inductor	= 2.16 kg
Estimated effective specific heat of the inductor	= 0.095 kcal/kg°C
Change of temperature	= 14 °C
Operating time	= 33 minutes
1 cal	= 4.184 kJoules
Heat generated	= ((2.65*0.444)+(2.16*0.095)) *14 * 4.184
	= 80.94 kJoules
Power of inductor	= 80.94 * 1000 / (33 * 60)
	= 40.88 Watt

STEADY STATE OPERATION CURRENT AND VOLTAGE WAVEFORMS

Current Ripple Waveform

When the arcjet PCU was tested with the resistive

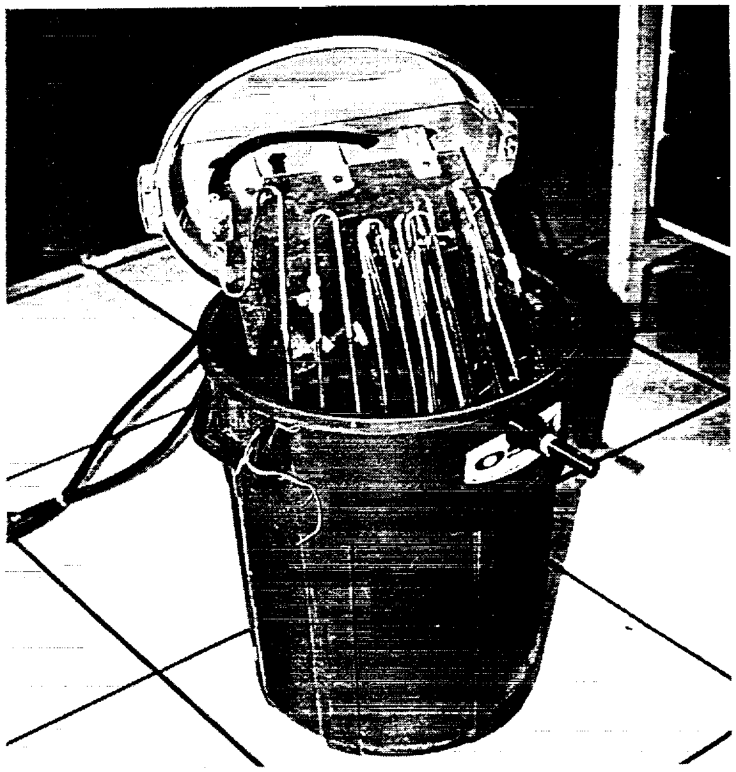


Figure 10. First Dummy Load

Figure 11. First Dummy Load

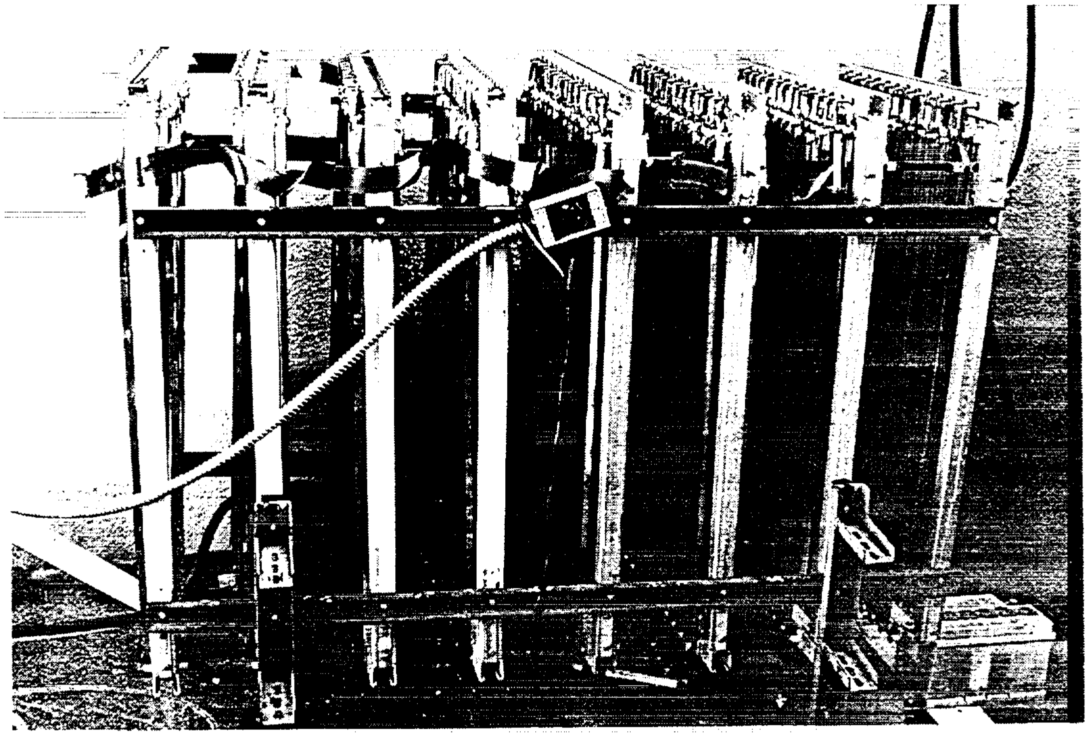


Figure 12. Second Dummy Load

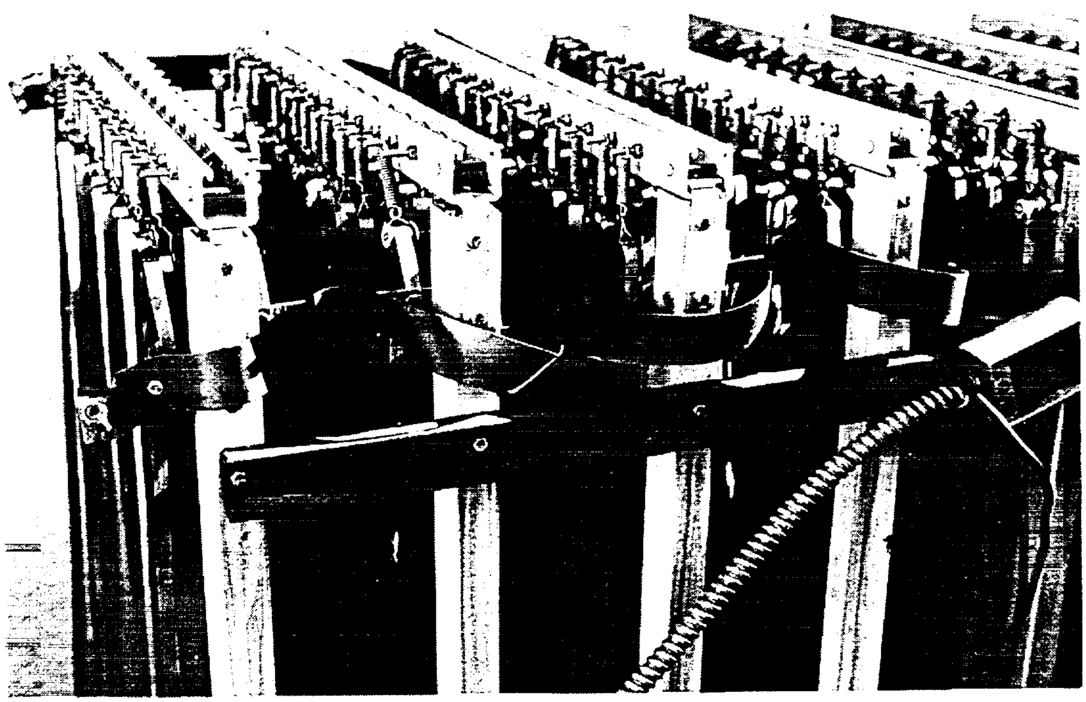


Figure 13. Second Dummy Load

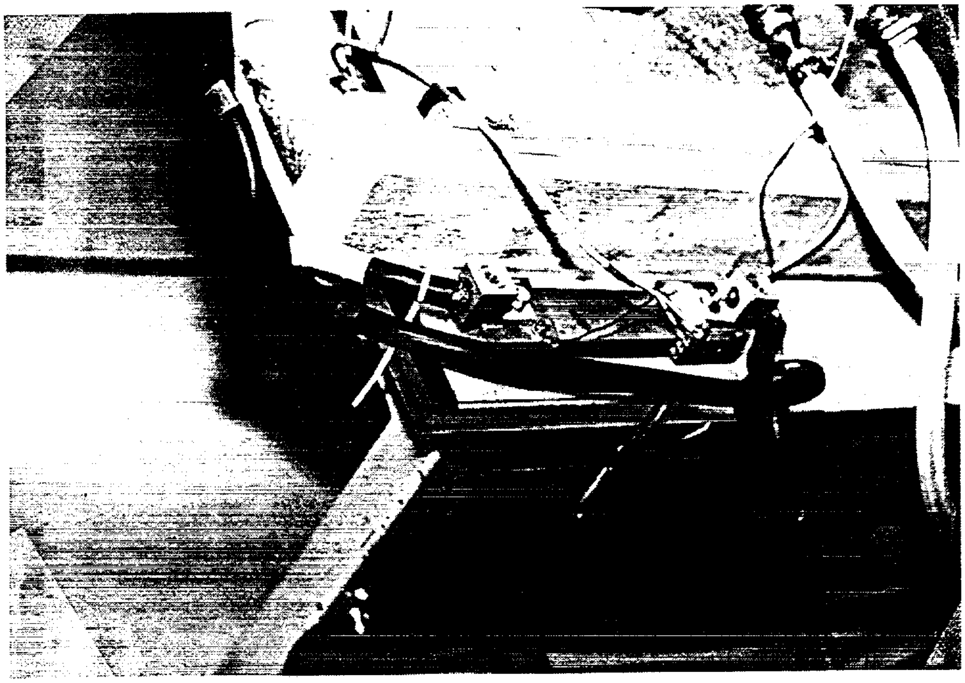


Figure 14. Input Current Shunt

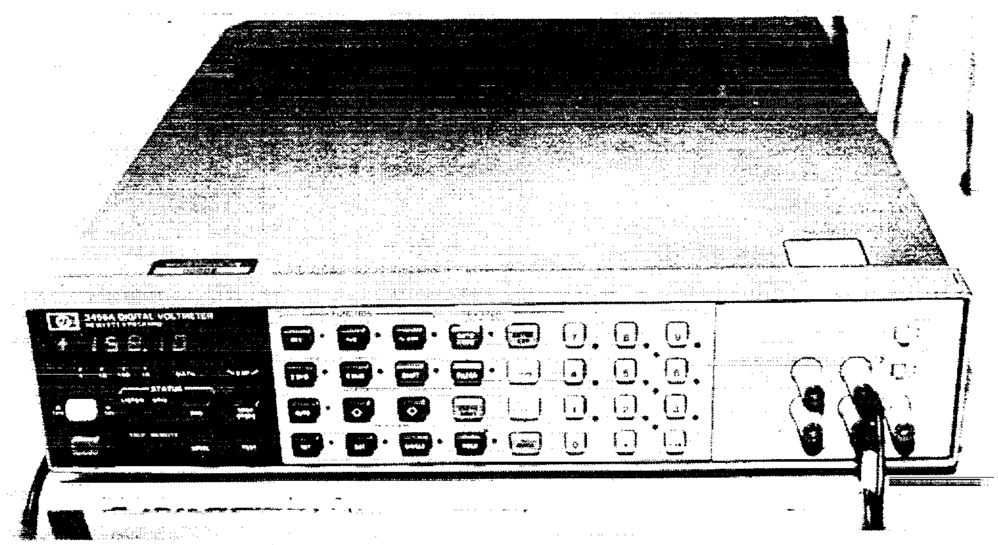


Figure 15. Hewlett Packard 3456A Digital Volt Meter

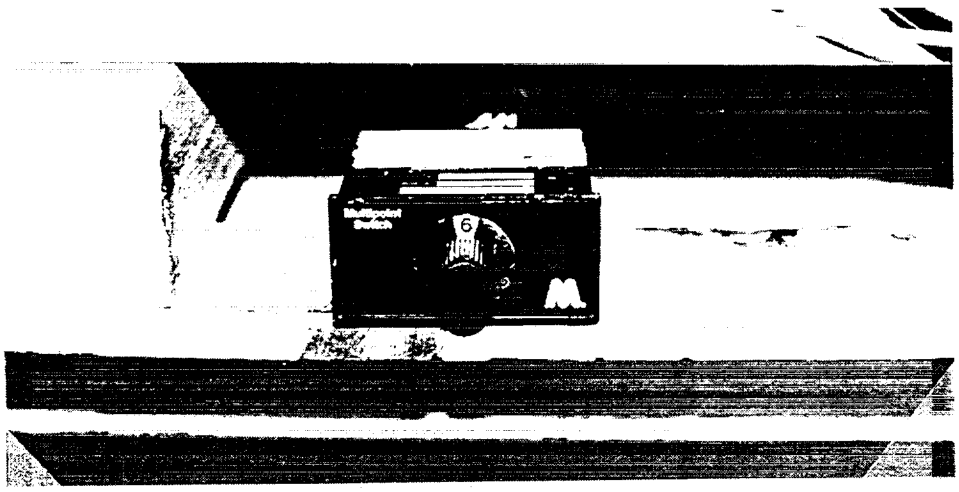


Figure 16. Multi-position Switch

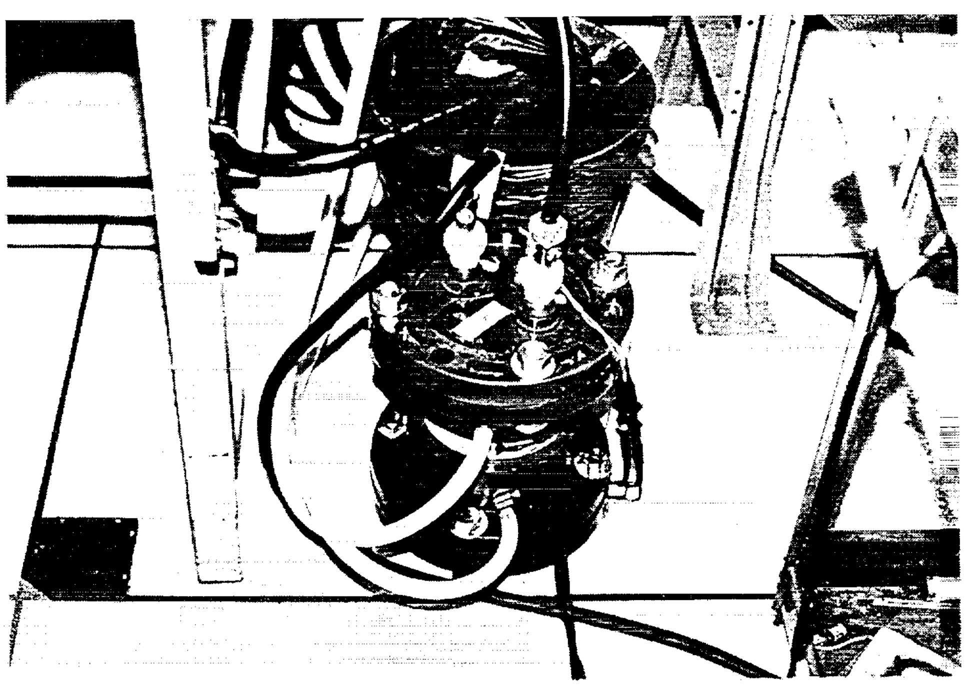


Figure 17. Water-cooled Shunt

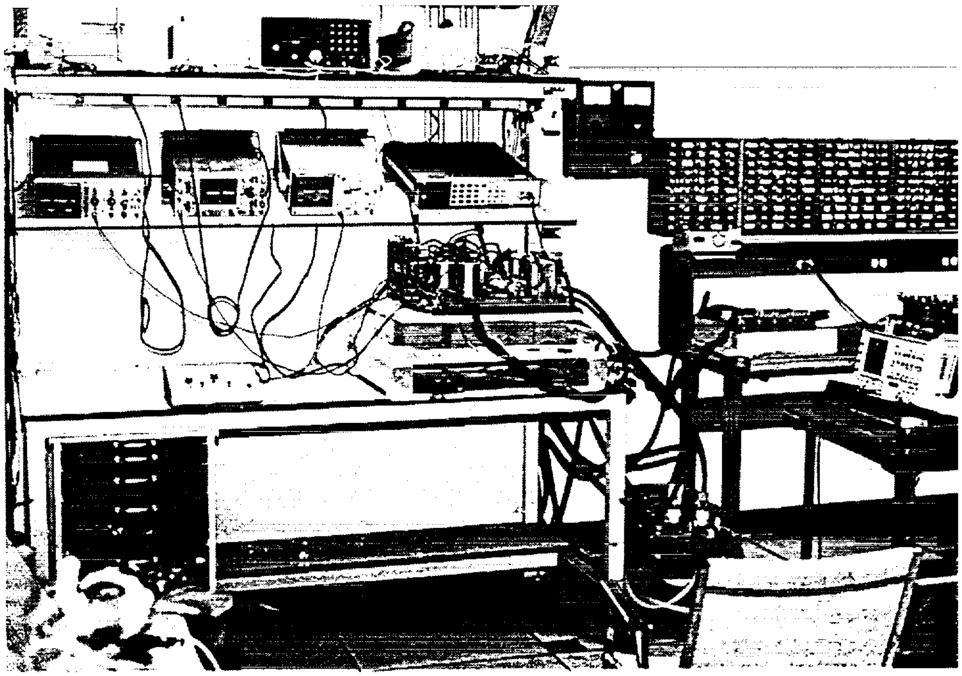


Figure 18. Efficiency Measurement Setup

Table 3. 30 kWe PCU Efficiency Measurement Data

V_{in} / V_{out}	I_{in} / I_{out}	P_{in} / P_{out}	Efficiency
150	47	7,050	94%
49.7	134	6,659	
150	68	10,200	95%
60.1	162	9,736	
150	90	13,500	96%
69.9	187	13,071	
150	118	17,700	96%
80.2	213	17,082	
150	148	22,200	96%
90.1	238	21,443	
150	179	26,850	97%
100.0	262	26,200	

Table 4. 30 kWe PCU Efficiency Measurement Data

Input Voltage	Input Current	Output Voltage	Output Current	P Output (w) / Input (w)	Efficiency	Corrected* Efficiency
157.3V	114.2A	101.1V	171.8A	17369.0 / 17963.6	96.68%	97.4%
156.9V	138.8A	111.4V	188.92A	21045.7 / 21777.7	96.63%	97.3%
156.4V	163.6A	121.26V	210.2A	24785.5 / 25587.04	96.68%	97.5%
156.3V	173.64A	125.3V	210.2A	26338.3 / 27139.9	97.00%	97.7%

* This number was adjusted from the measured efficiency by the correction factor between the input current shunt and output current shunt. The correction factor was obtained by measuring their voltages with the same current flow.

load, the output voltage and current waveforms had the same shape. Therefore, only the current waveforms are shown.

The amplitude of the ripple varied with the duty cycle. The three phases were fired 120° out of phase. Therefore, when the duty cycle was either 33.3% or 66.7%, the current ripples should cancel each other and have zero resultant ripple on the composite current. Figures 19 to 21 show some typical output waveforms at various duty cycles and power levels.

Source Waveform Drain

The drain and source voltage waveforms of the power MOSFET was of great interest to us because it showed the duty cycle, the stability of the PCU, and the voltage stress on the MOSFETs. The common failure modes of the MOSFETs were over voltage, over current, and over temperature. Because of the careful thermal design of the PCU and the real time response of the current-mode control, over-current and over-temperature were not likely to happen. Over-voltage became the most likely mode of MOSFET failure.

In the arcjet PCU, up to 100 A was being switched by the MOSFETs with about 200 ns switching time. Very high voltage spikes were generated at the moments that the MOSFETs were switched off. Even when a snubber circuit and metal oxide varistors (MOV) were put in to reduce the voltage spikes, the amplitude of the spikes still reached, or even exceeded, the Drain-Source breakdown voltage. Therefore, SPI always monitored the drain-to-source voltage waveform while operating the PCU at high power level.

Output Short Circuit Response

The need for a fast recovery in output current, when the load impedance suddenly goes to zero (short circuit), is discussed in detail in Technical Discussion section. The followings are the waveforms that indicate the improvement that SPI made under this program.

Starter circuit

Figures 24 and 25 show the voltage waveforms of the start pulse with an open load. This high voltage pulse is available to the thruster for starting the arcjet when the PCU is connected to the arcjet thruster.

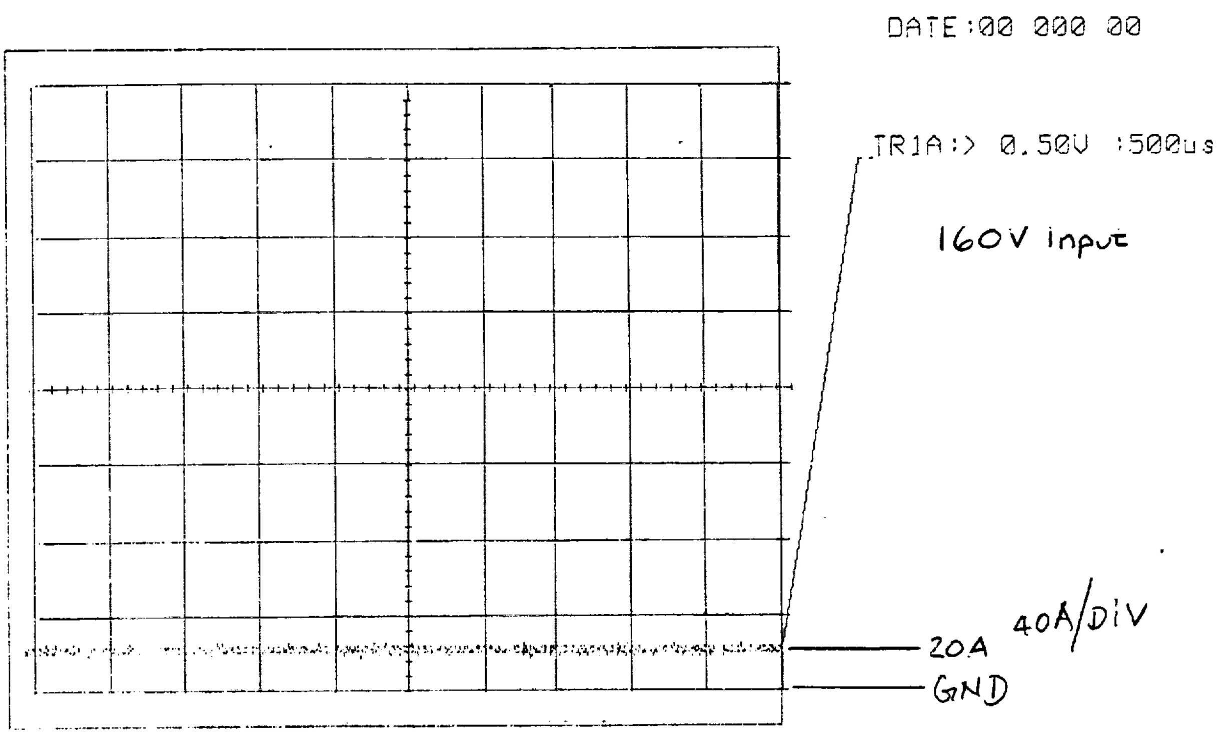


Figure 19. Output Current Waveform at 12.5% Duty Cycle and 200 W

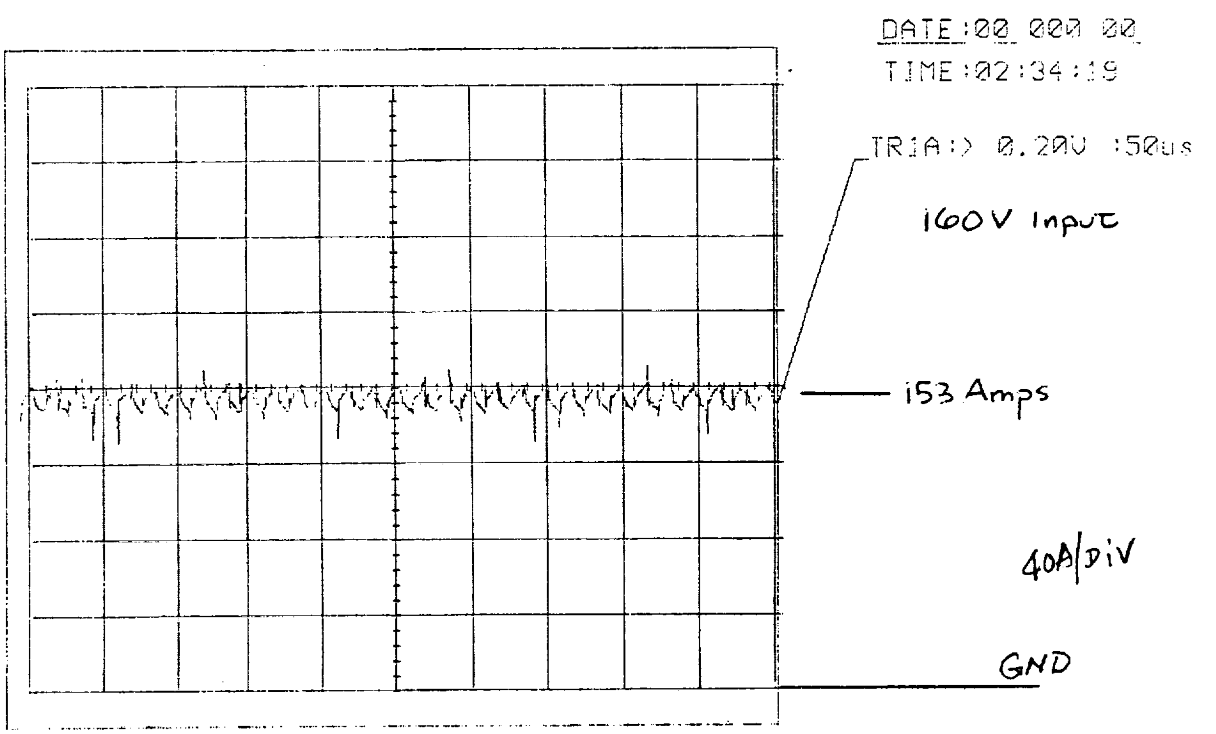


Figure 20. Output Current Waveform at 47.5% Duty Cycle and 12 kW

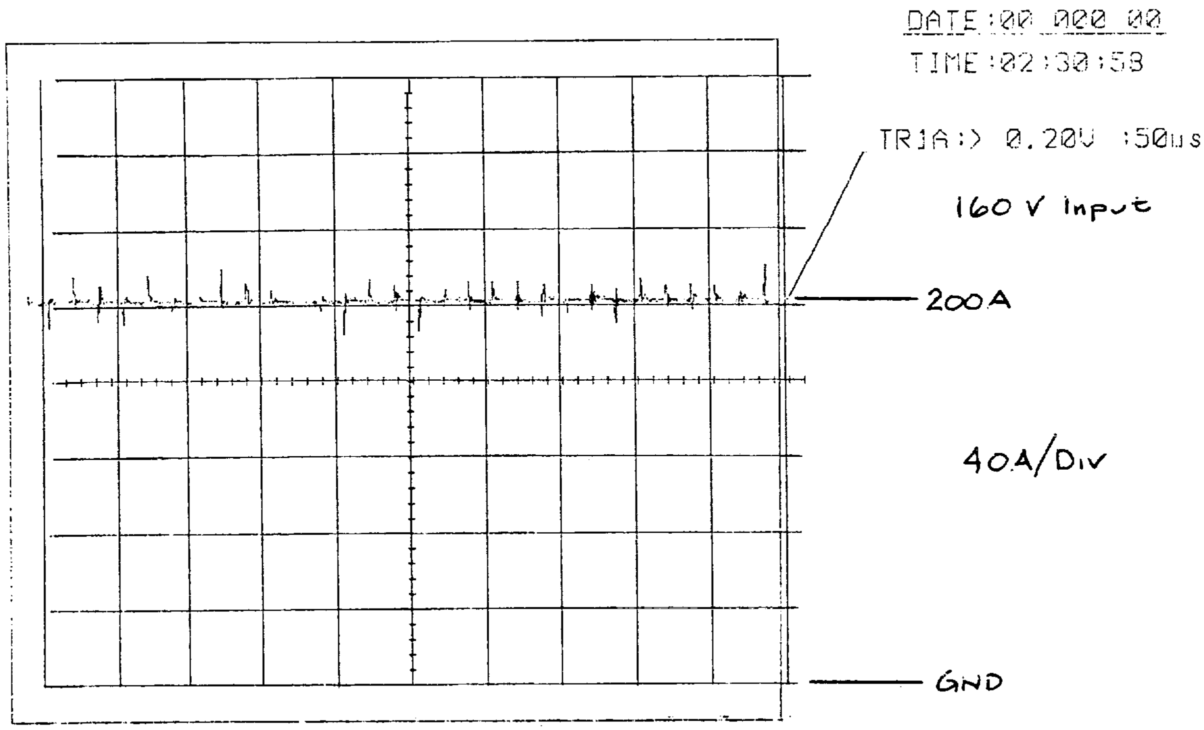


Figure 21. Output Current Waveform at 67% Duty Cycle and About 21 kW

Figure 26 is the voltage waveform of the start pulse when the output of the arcjet PCU is connected to the arcjet simulator, which consists of an SCR and a resistive load.

Start To Steady State Transition

As mentioned in previous sections, there could be a surge current during the startup transition. Surge current had been as high as 700 A when the PCU was first built. The surge current could cause excessive cathode degradation and shorten the useful life of the arcjet thruster. Efforts were undertaken to minimize the initial surge current, in terms of both magnitudes and durations. Even though the surge current was not completely eliminated, SPI is reasonably satisfied because the surge current seems too small to cause cathode damage. Figures 27, 28 and 29 show three startup current waveforms obtained in the same test with the same thruster. There was some randomness in the magnitude of surge current. The suspicion is that it was due to the variations in arc impedance.

TESTING OF 30 KW ARCJET PCU WITH ARCJET THRUSTERS

Two off-site arcjet tests have been performed on the PCU. The first one was conducted at NASA Lewis Research Center and the second one was conducted at Jet Propulsion Laboratory. Both of these tests were performed on a co-operative basis. Therefore, the technical objectives and the interests of these tests were not limited to PCU performance. For this program, the major objectives of these tests were to demonstrate the stable operation of the PCU with an arcjet thruster, the capability of initiating the arcjet with its build-in starter, and the endurance of the PCU.

Thanks to the support of NASA LeRC and JPL, SPI was able tc operate the arcjet PCU in both facilities and to obtain valuable test data. The following describes the test conditions, the results, and the performance data.

Testing at NASA LeRC

The test was performed in Tank 5 of the Electric Propulsion Laboratory. The thruster was a NASA LeRC

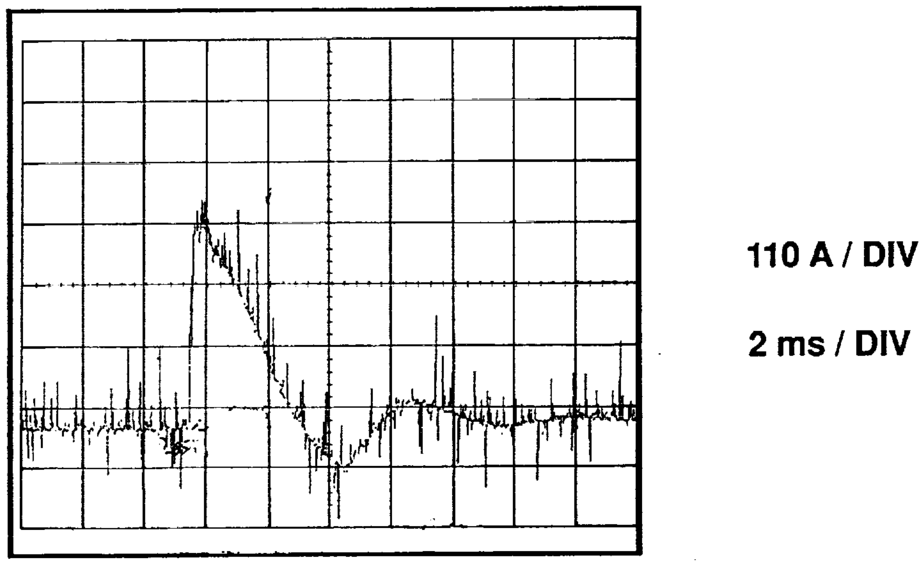


Figure 22. Short Circuit Response Before Improvement

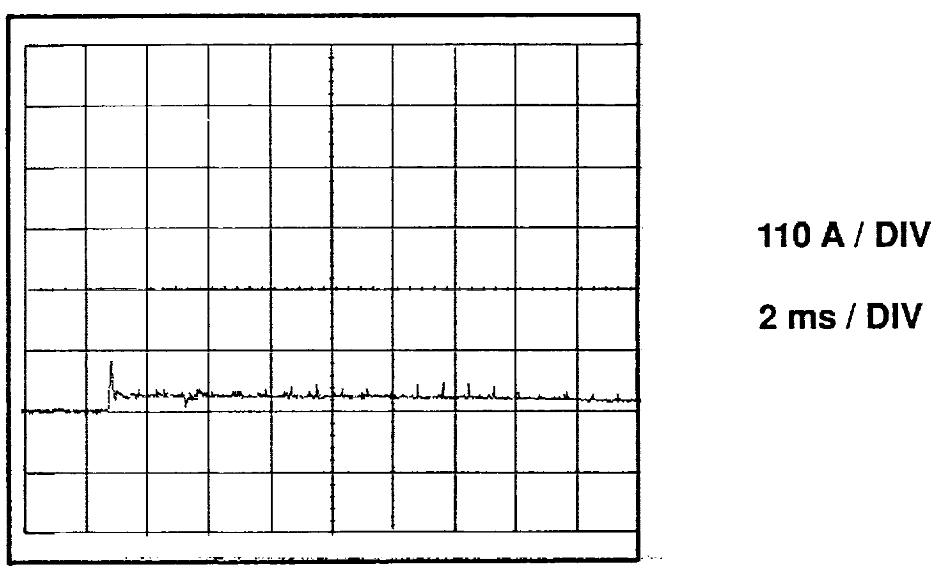


Figure 23. Short Circuit Response After Improvement

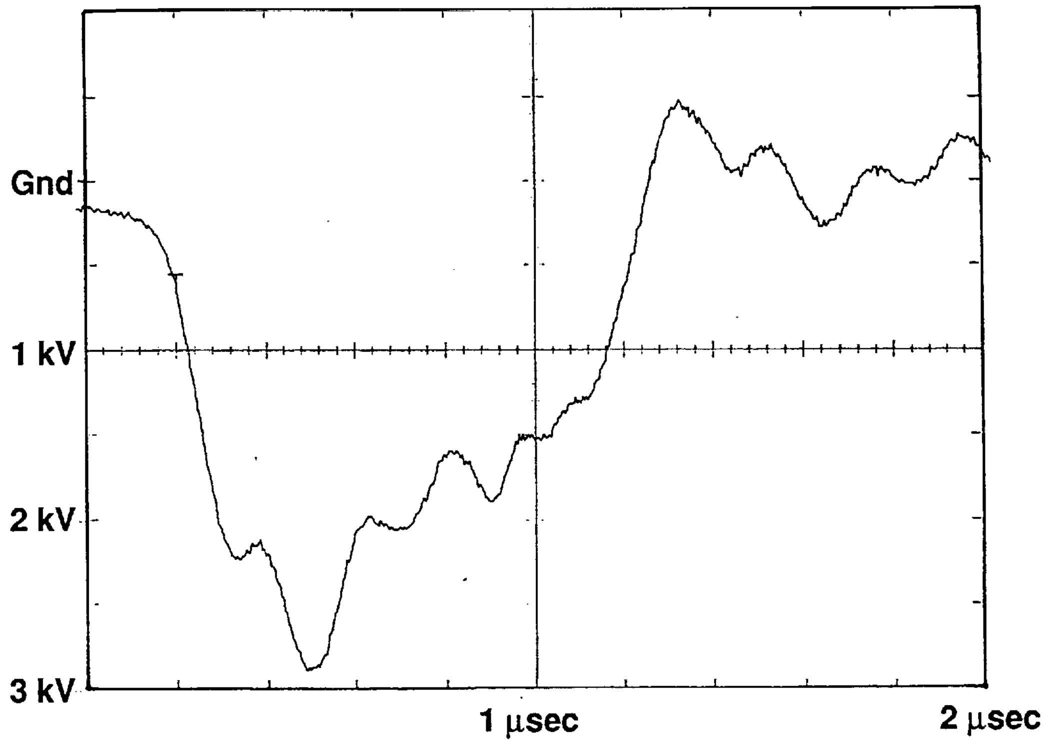


Figure 24. Open Circuit Start Pulse Waveform

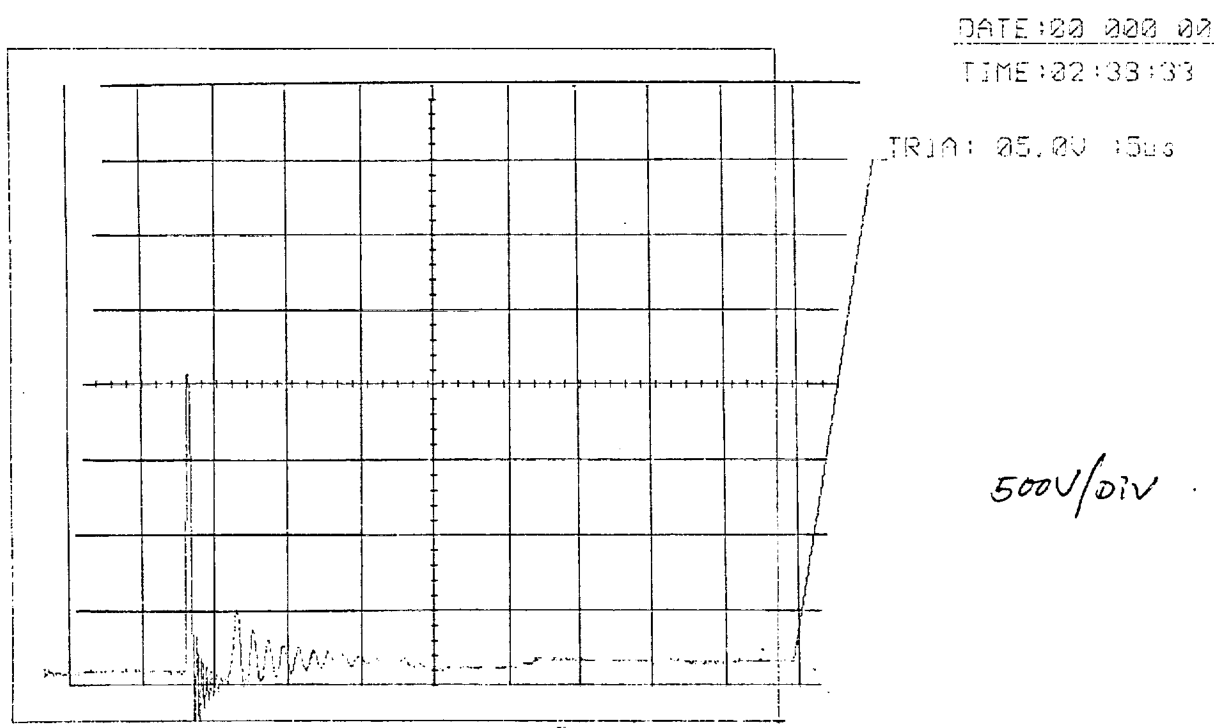


Figure 25. Open Circuit Start Pulse Waveform

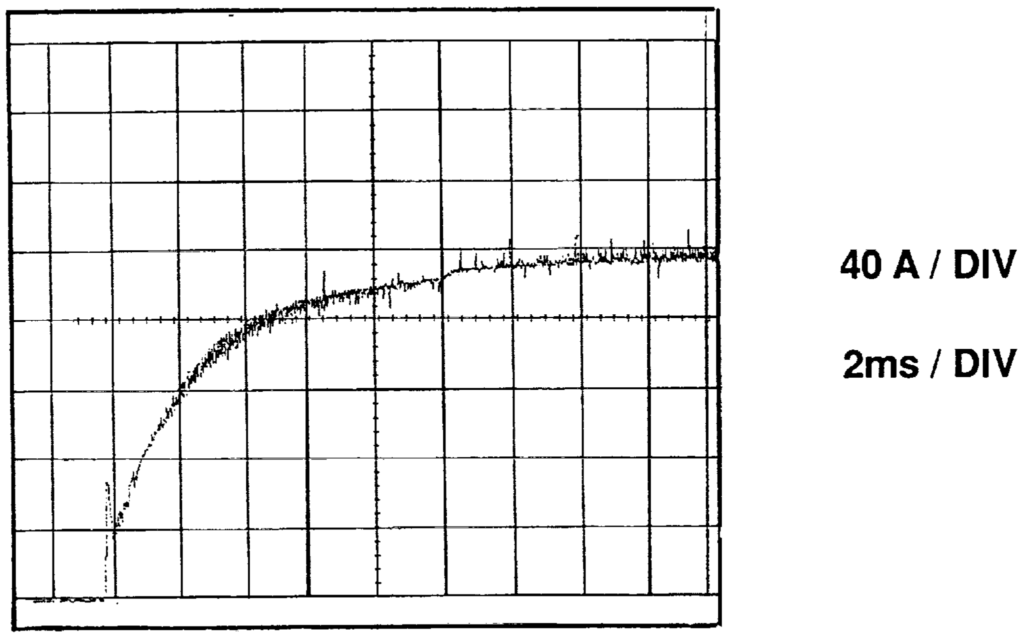


Figure 26. Start Waveform With Simulator (~4 msec Rise Time)

30 kW class arcjet thruster which was a scaled up model of the NASA LeRC low power arcjet thruster. The propellant used was hydrogen. Because the arcjet PCU II was originally designed for an Ammonia arcjet, SPI had some concern about operating the arcjet PCU with a hydrogen arcjet because of its higher operating voltage.

At the beginning of the test, SPI had difficulty in starting the hydrogen arcjet. It was later determined that the difficulty was related to the soft-start circuit. The initial current, which was controlled by the soft-start circuit, might have been so low that its corresponding voltage was higher than the PCU limit. Even if the arc might have started momentarily, it could not be maintained because of the low current demanded by the soft-start circuit. A multi-position switch was mounted on the front panel to select the rate of rise of the current of the soft-start circuit. Unfortunately, even the fastest rise time setting was still not fast enough to maintain the arc.

Based on this hypothesis, SPI modified the control PCB to reduce the rise time. The arcjet started after the rise time was reduced to about 400 µsec. The hydrogen arcjet started on every few attempts. The degree of difficulty of starting the arcjet was related to the mass flow rate.

Since the difficulty in starting the arcjet was due to the excessively low current set by the soft-start circuit, SPI increased the initial current set by the soft-start circuit. However, the ammonia arcjet has a lower voltage than the hydrogen arcjet. It was decided not to modify the PCU until the arcjet PCU was tested with an ammonia arcjet.

Even though the soft-start circuit had caused difficulty in starting the arcjet, it is important to retain the soft-start function to avoid any thermal shock to the arcjet thruster. More study is needed to develop a soft-start strategy that will not cause the startup problem. Due to the slow response nature of this function, SPI does not feel that this function needs to be an integral part of the PCU. In they're opinion, this function may be better served in the higher level controller/computer because software is more flexible and easier to modify.

The total operating time of the PCU was about 30 minutes. The arcjet was started at about 10 kW and increased gradually to 24 kW. The test was then terminated when some unrelated instruments inside the same tank were heated up by the plume. Figure 30 shows the arc from the side viewing port. Figure 31 shows the plume from the top viewing port.

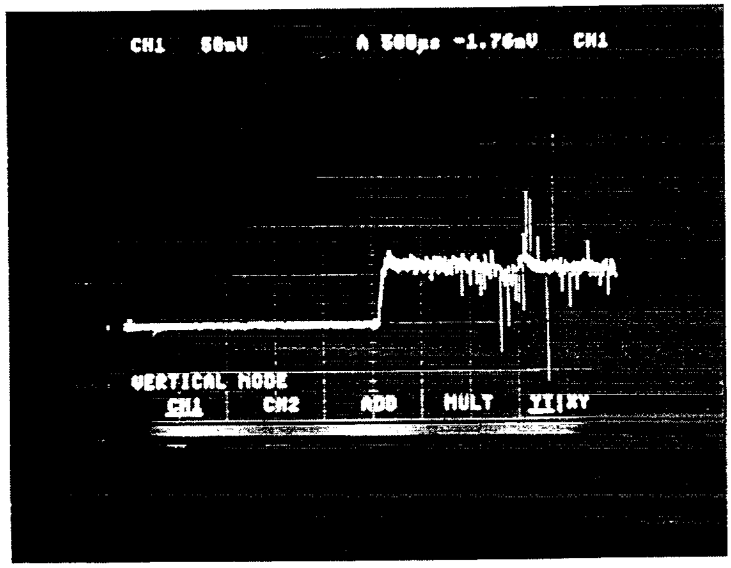


Figure 27. Startup Current Waveform

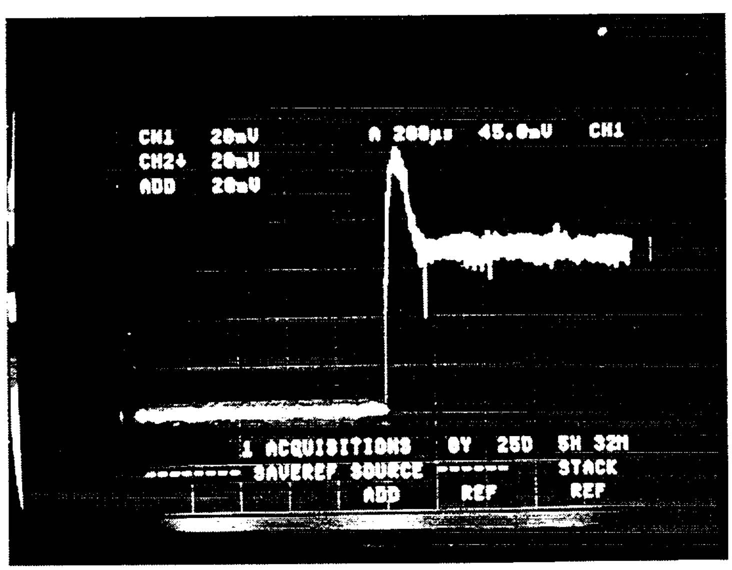


Figure 28. Startup Current Waveform

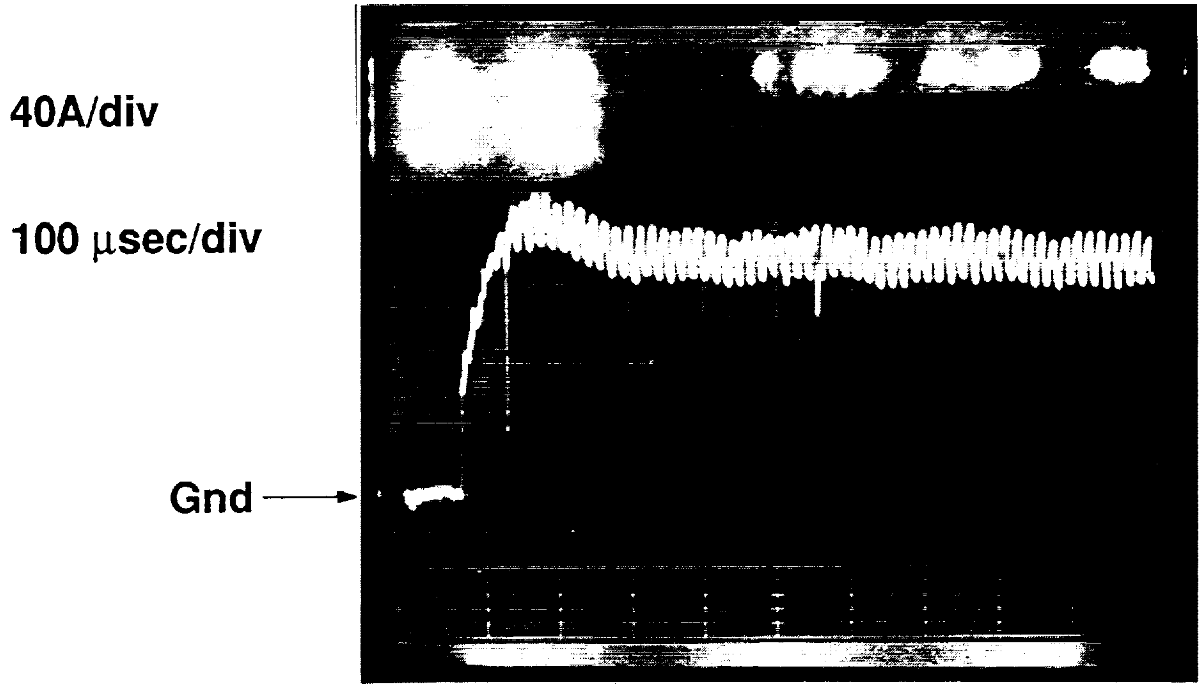


Figure 29. Startup Current Waveform

Testing In JPL

Unlike the test at NASA LeRC, the PCU test at JPL was performed with an ammonia arcjet, for which the arcjet PCU was originally designed. The objective of JPL was to characterize the performance of an ammonia arcjet at different power levels with different propellant flow rates. SPI had two objectives in this test. The first one was to test the capability of our build-in starter circuit with ammonia arcjet. The second one was to operate the arcjet PCU uninterrupted for a long period of time.

The Arcjet PCU

The test was performed with PCU I.2 because PCU II was not available. PCU I.2 was constructed in Phase I of this contract. Even though this arcjet PCU was built two years before, it had been modified with all the latest circuit improvements that were developed during this contract. Therefore, the test result of this PCU should reflect the performance of the other two PCUs including PCU II. The key difference between PCU I.2 and PCU II is the number of MOSFET modules. PCU II used two MOSFET modules per phase while PCU I.2 used only one MOSFET module per phase. Therefore, SPI would expect PCU I.2 to be somewhat less efficient and less reliable. However, this difference would not affect the input/output characteristic and functionality of the PCU.

When SPI performed the final in-house check-out test on this PCU before it was shipped to JPL, it observed some higher than normal fluctuation at the 66.7% duty cycle. (Please refer to the Technical Discussion section for details.) As mentioned in the Technical Discussion, the problem could be caused by many possibilities that are not easy to identify. The cause of the duty cycle fluctuation was not immediately identified.

Because of the time constraint at the JPL facilities and the testing schedule, SPI faced the decision of either missing this opportunity window to test the PCU or going ahead to test the PCU despite an unknown but seemingly minor circuit problem. The fluctuation, somewhat higher than normal, caused the current to flucturate randomly up to 5% of the average current. This should not significantly affect the performance of the thruster. In fact, the unknown cause of the fluctuation was more worrisome than the fluctuation itself. On the other hand, the problem could well be so benign that it would not cause any damage other than some

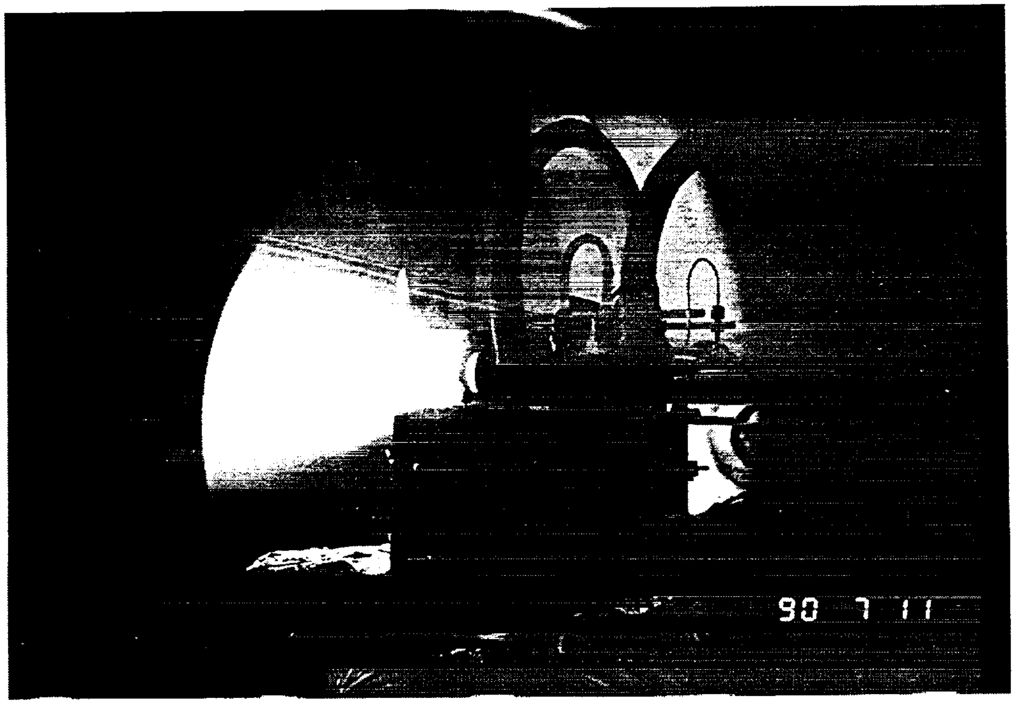


Figure 30. NASA-LeRC Arcjet Test Viewed From Side Viewing Port

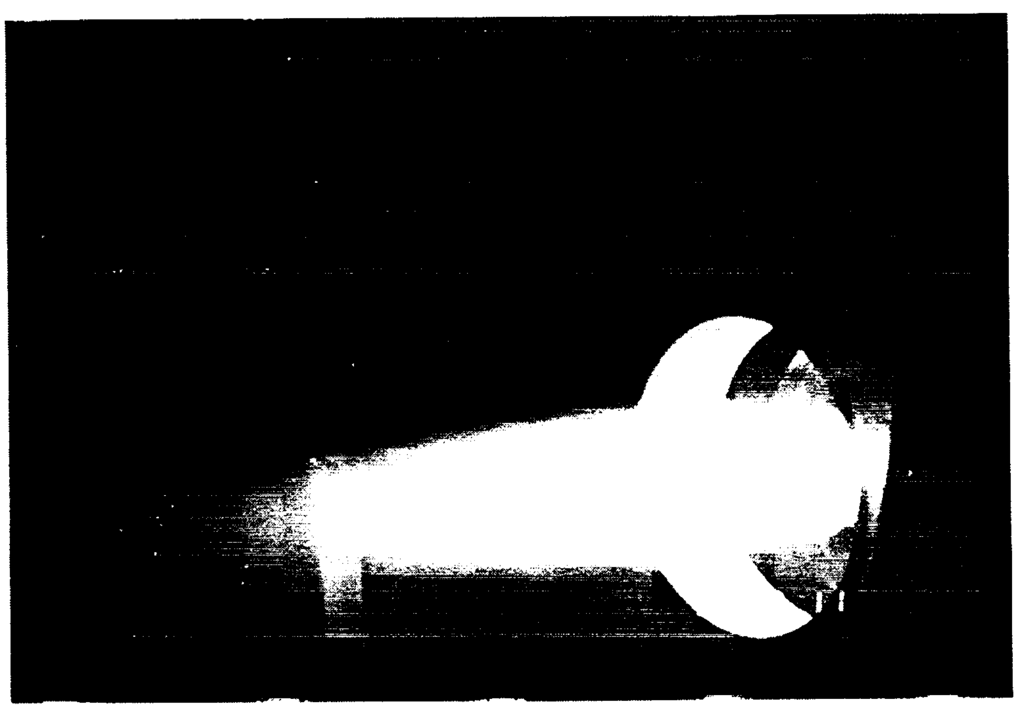


Figure 31. NASA-LeRC Arcjet Test Viewed From Top Viewing Port

random ripple in the arcjet current at 66.7% duty cycle. Because SPI had been waiting for the JPL test for a long time, it decided not to give up this opportunity and ship the PCU for ammonia arcjet testing. It was suggested JPL to avoid prolonged operation of the PCU at 66.7% duty cycle.

The Starter Circuit

The build-in starter circuit was capable of generating a narrow high voltage pulse that is slightly above 2000 V. The pulse duration is in the order of 300 nsec. A waveform of this pulse is shown in Figure 32.

The starter circuit of the same design had been tested at NASA LeRC with a hydrogen arcjet. The feasibility of the arcjet startup was demonstrated with some difficulties. During the NASA LeRC test, SPI was able to start the arcjet after modifying the soft-start circuit. It expected to start the arcjet easier this time for two reasons. First, the problem caused by the soft-start circuit was eliminated. Second, the ammonia arcjet has a lower operating voltage and therefore a lower breakdown voltage was expected.

During this test, there was no trouble in starting the ammonia arcjet with a seasoned thruster. However, the starter failed to start a new thruster on several occasions. The exact cause was not known. However, the difficulty of starting reduced rapidly after the arcjet was used.

Endurance Test

Although SPI has tested their arcjet PCU in-house at or near full power for tens of hours, it had never attempted to operate the PCU overnight. The facility at JPL had performed many long hour endurance tests for arcjets and it had an automatic monitoring and safety system to allow operation of an arcjet system unattended. This was a good opportunity for SPI to demonstrate the reliability and the durability of the arcjet PCU.

The arcjet system was operated at 20 kWe continuously for 200 hours. Then the system was operated at 30 kWe for another 8 hours before the system was shut down by the PCU safety circuit, which detected an 82% duty cycle. (The PCU input was 165 V therefore the maximum allowable output voltage was 135 V.) The arcjet was later restarted and operated at 25 kWe for another 160 hours until the arcjet voltage dropped to 70 V due to cathode degradation. The test was then terminated voluntarily by JPL personnel.

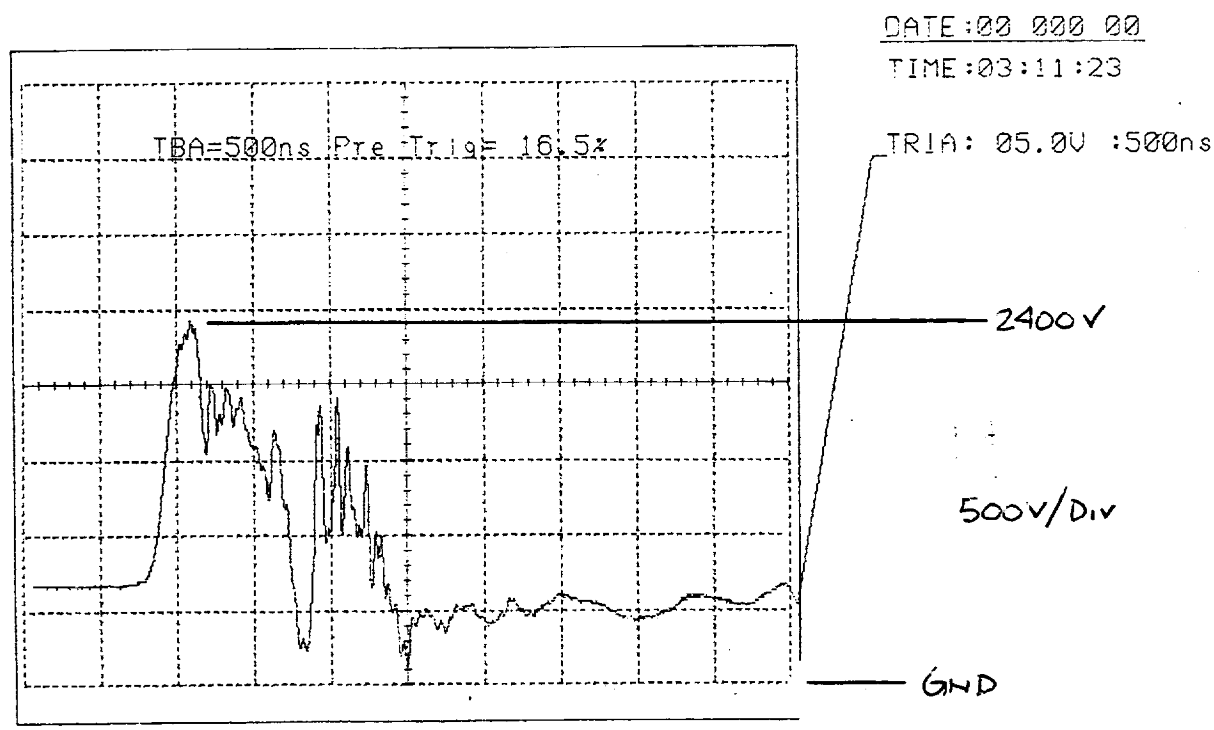


Figure 32. Starter Circuit Pulse Waveform

CONCLUSIONS

Achievements

A 30 kWe class arcjet PCU was designed, built, and tested with both a resistive load and arcjet thrusters. The PCU is also equipped with a built-in ignition system, which has successfully started arcjets inside vacuum chambers. Our arcjet PCU has operated at or near full power for many hundred hours with no sign of degradation. Output short circuit problems, which had caused power component failure earlier, have been addressed and resolved. The functionality and efficiency of the approach has been successfully demonstrated. The arcjet PCU design is now ready for further development into a flight qualified system.

Areas Requiring Future Work

The PCU ignition system still did not start the arcjet consistently. The requirement depends on the thruster design and the propellant. There is a need to better define the start pulse requirement for a specific application. Knowing exactly what the minimum requirement is of the high voltage pulse is more difficult than designing and building the electronic circuit to generate that pulse.

This PCU uses a simple buck topology which make the PCU reliable, highly efficient, compact and light weight. However, it lacks the input-output D.C. isolation and the flexibility of matching any arcjet voltage to different kinds of bus voltages. If these restrictions cause serious compromises in the system design, a PCU design with an isolation transformer may be a better choice. This design has been used in low power arcjet systems. Further development is needed for the high power system.

In order to perform its function successfully in a spacecraft, the PCU must be electromagnetically compatible with all the other electronic instruments on broad. This requires the PCU design to conform with a properly specified EMI requirements. Even though much effort has been spent on minimizing the EMI, there was no intention to make the existing arcjet PCU conform to any particular EMI specification. This is certainly an area that requires additional work before the PCU could be used in space.

REFERENCES

1. S. Wong and E.J. Britt, "High Power Arcjet Power Conditioner" AIAA-88-3101
2. Charles J. Sarmiento and Robert P. Gruber, "Low Power Arcjet Thruster Pulse Ignition" AIAA-87-1951
3. Private Conversation with Joe Cassady of Rocket Research Company.

ACKNOWLEDGEMENT

This work is funded by Innovative Science and Technology Office of SDIO (SBIR-Phase II) and technically managed by NASA Lewis. SPI would like to acknowledge the technical guidance from contract monitors, Dr. Frank Curran and Mr. John Hamley. It would also like to acknowledge the cooperation and support from NASA LeRC and JPL for arcjet testings at their facilities.

APPENDIX A
(Excerpt from a letter to Mr. R. Gruber of NASA-LeRC from Mr. E.J. Britt of SPI)

Turning now to the issue of circuit isolation to avoid stray currents from the arcjet plume to the spacecraft chassis: It is our contention that if either the anode or the cathode of the arcjet is connected to the spacecraft chassis ground, a transformer in the PCU to provide DC isolation will not be effective. Enclosed for purposes of discussion are several circuit diagram sketches showing both isolated and non-isolated PCU concepts with various portions of the circuit connected to ground.

Referring to Figure A1 in this group of sketches, note that even though the PCU has a DC isolation transformer, current can still flow from the arcjet plume to the chassis and return through the connection of the anode to ground. In this case, the cathode is at a negative potential of about −100 V with respect to the spacecraft, and relatively large quantities of electron current could possibly flow from the plasma to the spacecraft.

In Figure A2 a similar situation is depicted, but the cathode is grounded instead of the anode. In this case the anode floats at approximately +100 V with respect to the spacecraft, and ion current may flow from the plasma plume to the spacecraft structure. While the magnitude of the ion current is expected to be much less than the electron current (circuit in Figure A1); it may still be damaging since the ion bombardment could sputter erode surfaces on the spacecraft.

Note that in both of these cases the DC isolation provided by the transformer does not prevent the current flow. Furthermore, even with a transformer isolation there will still be capacitive coupling between the arcjet and the chassis, as well as between the windings of the transformer. This coupling will permit some degree of AC (ripple) current to flow to the chassis.

As shown in Figure A3, an arcjet/PCU combination connected to an ungrounded source of electric power has no return path for current conducted to the spacecraft chassis. In this case, the spacecraft will be charged to a floating potential where all currents will stop. We feel that this would be a preferred arrangement to avoid stray currents. However, it would still be necessary to insulate or shield all portions of the circuit (including the bus bars) from possible current paths to the arcjet plumes. An isolation transformer is not needed in this case.

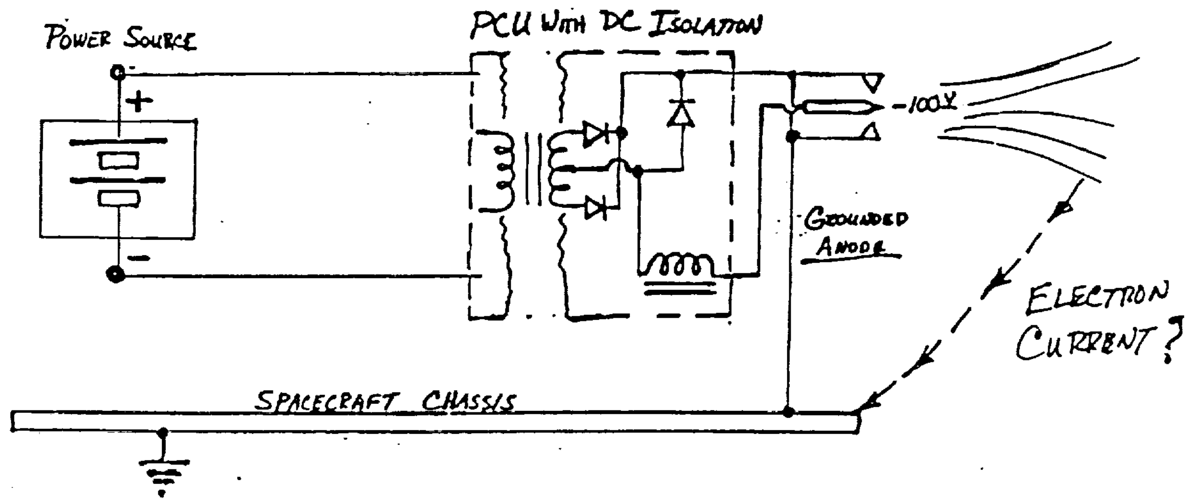
If the negative terminal of the power source is connected to spacecraft ground with a direct coupled PCU as shown in Figure A4, the arcjet anode will operate at a potential equal to the source voltage (+200 V in SP-100) above the spacecraft chassis. The arcjet cathode will be at potential 100 V less, or about +100 V above the chassis. Since the plasma plume is expected to assume some potential between that of its anode and cathode (probably closer to the anode), this situation might permit ion currents to flow from the plasma to the spacecraft.

If the power source has a center tap ground (as is planned for the SP-100 thermoelectric generator), the potential of the arcjet will be as shown in Figure A5; i.e., the anode will be +100 V above the spacecraft chassis and the potential of the cathode will be approximately the same as the spacecraft chassis. Again, it would be possible for ion current to flow in this situation, however, the driving voltage is only half as much as would result from connection shown in Figure A4.

Because of the low mobility of ions, compared to electrons, and because the path of current flow from the arcjet plume to the spacecraft is expected to be a high impedance, these ion currents may very well be small enough to cause no trouble. If the ion current proves to be troublesome, isolation in the PCU may be required. However, the DC isolation may be provided in any event if the power system uses a DC-DC converter of the type being developed by SPI for voltage step-up of the output from direct conversion space reactors. A sketch illustrating this type of arrangement is shown in Figure A6.

Since SPI has built transformer-coupled arcjet PCU's (3 kWe voltage-boost PCU sold to RRC) as well as direct coupled buck regulator units, we could readily modify our 30 kWe designs to include transformer isolation if it becomes necessary. We are presently advocating a circuit architecture for the arcjet PCU which is simpler and more efficient than a transformer isolated design. It must be recognized that a substantial increase in weight and loss of efficiency will result from the transformer coupled architecture as opposed to the direct buck regulator. Further definition of the specific circuit for power system, and probably some space experimentation will be required to clarify the reality of the need for DC isolation. This is particularly true since a voltage step-up inverter may be used with a thermoelectric or thermionic reactor system to protect the high temperature insulators in the conversion system.

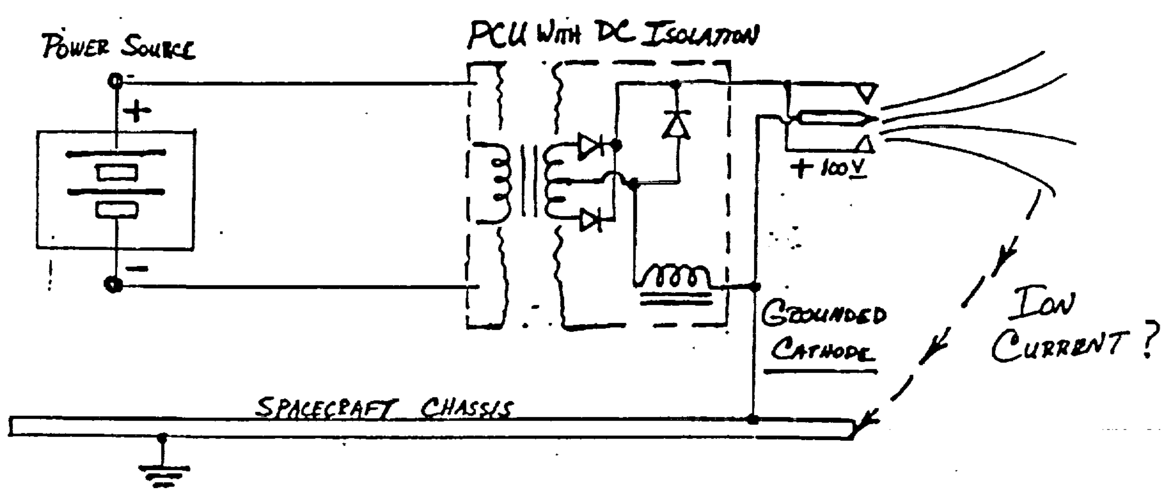
We acknowledge that the question of isolation is an open, undecided issue; but it is not consistent to worry about isolating the power supply if there is a plan to ground either the anode or the cathode of the arcjet to the chassis. Further experimentation exploring plasma stray current effects needs to be undertaken — possibly in space to avoid the effect of a vacuum tank. Perhaps we should investigate various types of plume shields at different potentials to avoid undesired currents to the spacecraft chassis. We will be interested in continued interaction to further develop a consensus of design philosophy related to these questions.



Large currents (electrons) may flow from the plasma plume to the chassis.

Transformer isolation is not effective.

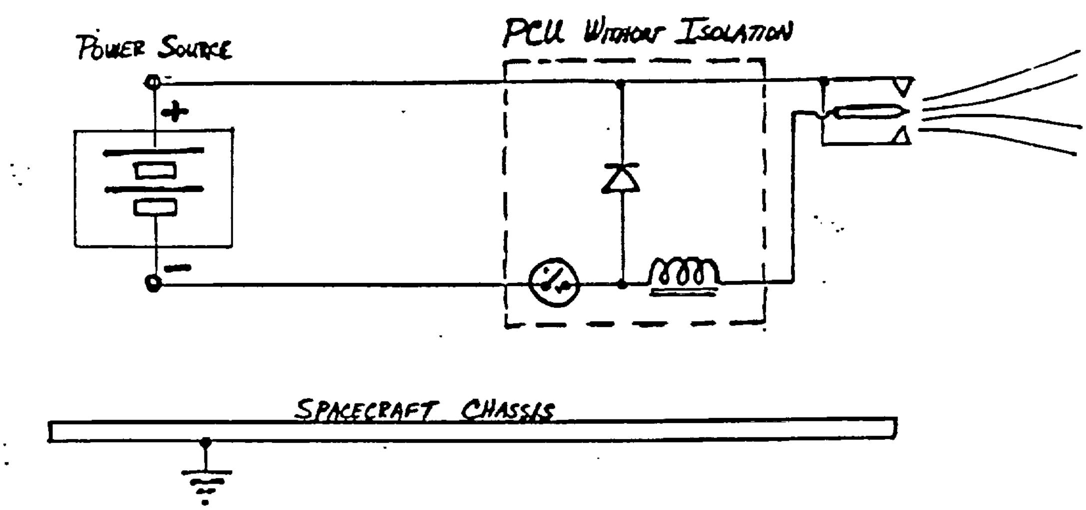
Figure A1. Grounded Anode Configuration



Small currents (ion) may flow from the plasma plume to the chassis.

Transformer isolation is not effective.

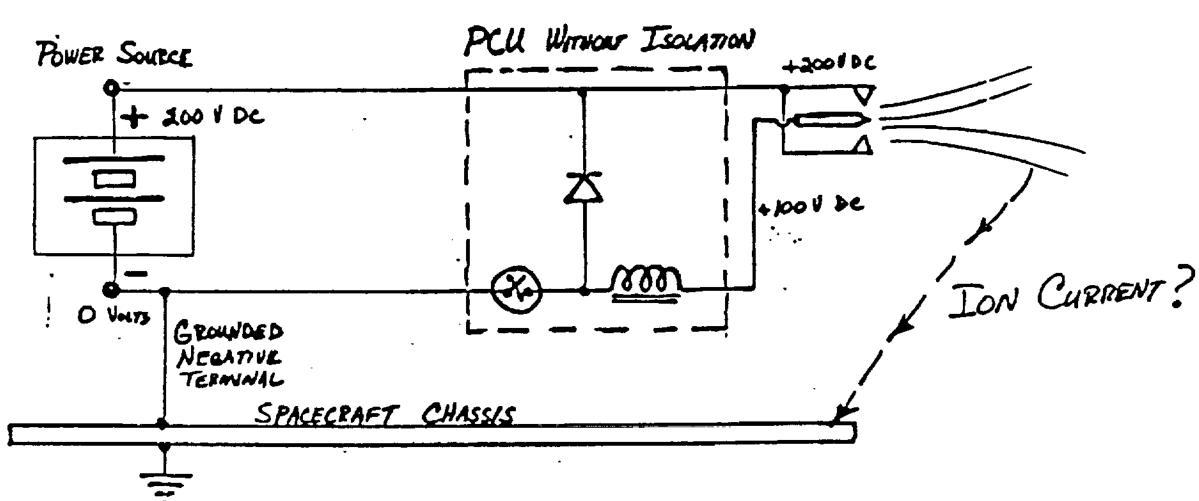
Figure A2. Grounded Cathode Configuration



No possible current path from the plasma plume to the chassis.

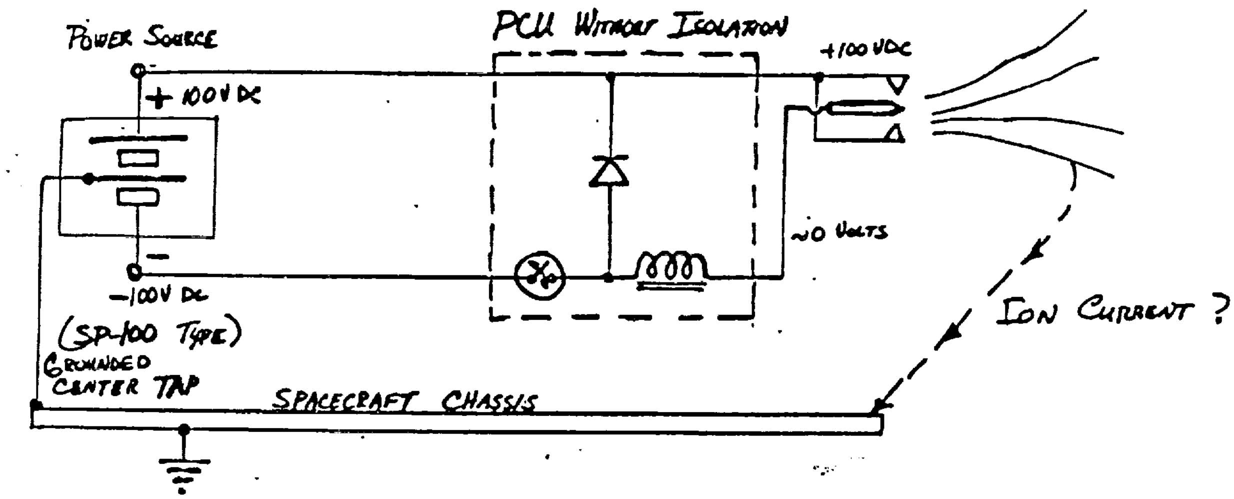
Preferred arrangement, transformer isolation is not needed.

Figure A3. Ungrounded Configuration



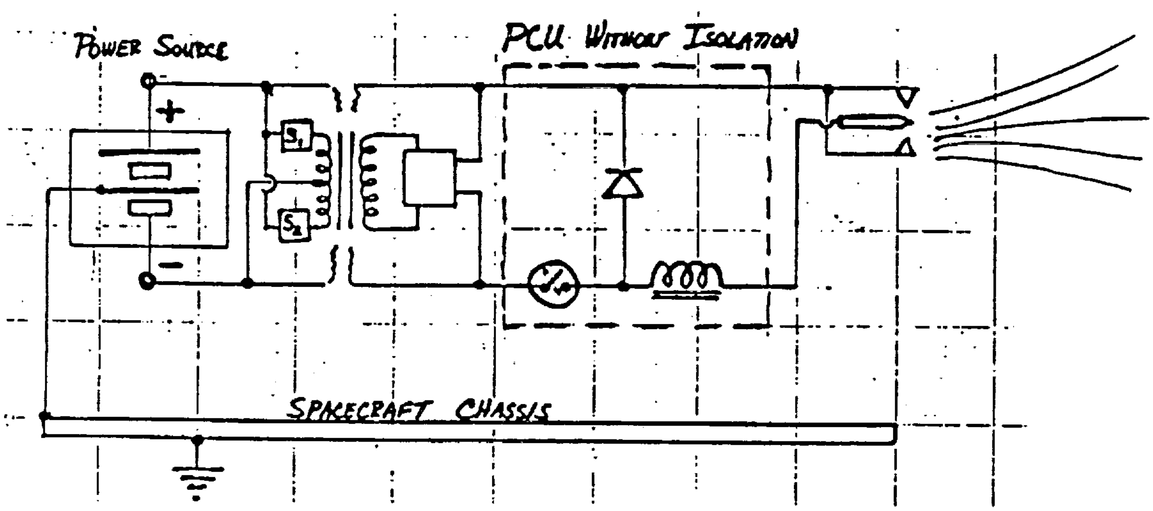
Ion currents from the plasma plume to the chassis are possible.

Figure A4. Grounded Negative Terminal Configuration



Ion current may flow from the plasma plume to the chassis.

Figure A5. Grounded Center Tap (SP-100)



Isolation provided by transformer in bus bar PCU. No paths for stray currents from the plasma plume to the chassis are possible.

Figure A6. Power Source with Voltage Step-up

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 1994

3. REPORT TYPE AND DATES COVERED
Final Contractor Report

4. TITLE AND SUBTITLE
Non-Isolated 30 kW Class Arcjet PCU

5. FUNDING NUMBERS
WU-506-42-31

6. AUTHOR(S)
See-Pok Wong and Edward J. Britt

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Space Power, Incorporated
621 River Oaks Parkway
San Jose, California 95134-1907

8. PERFORMING ORGANIZATION REPORT NUMBER
E-7426

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR-189148

11. SUPPLEMENTARY NOTES
Project Manager, John A. Hamley, Space Propulsion Technology Division, organization code 5330, (216) 433-7430.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 20

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

A 30 kW class arcjet Power Conditioning Unit, PCU, was built and tested on this Phase II SBIR contract. The PCU is an improved version of two previously developed PCU's. All of these units are 3-phase, 20 kHz buck regulators with current mode feed back to modulate the duty cycle to control the arcjet current at any selected operating point. The steady state control can assure arcjet stability despite the negative dynamic resistance of the arc discharge. The system also has a circuit to produce a high voltage start pulse to breakdown the gas and initiate the arc. The start pulse is formed by temporarily switching a short current path across the output terminals with a special solid state switching array. The switches then open rapidly, and the energy stored in the output inductors of the buck regulator produces a pulse of ~2500 V for ~500 nsec. The system was tested and modified until the transition to steady operation occured after start up with a very small surge current overshoot. The system also can withstand a direct short circuit across the output without damage. The automatic feed back control simply reduces the duty cycle to hold the current at the set point. When the short is removed the full power output is immediately restored. This latest version arcjet PCU is conduction cooled to remove waste heat by conduction to the base plate. This unit is closer to flight a type of design than the previous functional bread boards. Waste heat is small because the PCU has a very high efficiency, ≥96%. The PCU was extensively tested with resistor loads to simulate operation with an arcjet. The unit was tested with ammonia arcjets at the Jet Propulsion Laboratory. Approximately 400 hours of testing were completed, with several starts. Many hours were also demonstrated with resistive loads. Some testing with hydrogen arcjets was also carried out at NASA LeRC. This system concept is now the design base for the ATTD program.

14. SUBJECT TERMS
Arc-jet; Electric propulsion; Power processing

15. NUMBER OF PAGES
40

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102